
Conserving Giraffe in a Climate Changed World

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Abstract

Giraffe have faced large population declines over recent decades. As global temperatures rise, conservation actions increasingly need to account for projections of climate change impacts. Previously classed as one species, taxonomic updates categorise giraffe into four distinct species, with potential implications for conservation management. This thesis examined the exposure and projected impact of climate change on each species of giraffe, investigating the impact of projected changes in mean climate, extreme events, and non-climatic anthropogenic impacts. An initial analysis of projected climatic changes revealed consistent warming trends across all species' and subspecies' ranges, with more variable trends in precipitation. Novel climates are projected to emerge in most current giraffe geographic ranges under higher global warming levels. Species distribution models (SDMs), developed to project areas of suitable climate at global warming levels up to 3.6°C above pre-industrial levels, showed large decreases in suitable range under increasing global warming for each species. All species are projected to retain at least 24% of their current geographic range as areas of climate refugia at the highest warming level. Climate suitability projections were then integrated with projections of other ecological and anthropogenic pressures to spatially prioritise conservation areas using Zonation software. This analysis revealed key areas of stability or vulnerability, highlighting regions where increased adaptation or protection efforts are needed, particularly where protected areas are absent. These outputs were made available to conservationists (e.g., the Giraffe Conservation Foundation) through GiraffeClim, a user-friendly web application designed to support real-time, climate-informed decision-making. The research outputs were discussed in the context of publicly available giraffe conservation action plans,

highlighting key climate-change threats and potential conservation actions for each species and subspecies of giraffe. This thesis provides a climate-resilient conservation guide for giraffe, offering both strategic insights and actionable tools to support long-term species persistence under global change.

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List of Abbreviations

ABF	Additive Benefit Function
AR6	Assessment Report 6
AUC	Area Under the Curve
CAZ	Core-Area Zonation
CMIP	Coupled Model Intercomparison Project
ECE	Extreme Climatic Event
ESA CCI	European Space Agency Climate Change Initiative
GAM	Generalised Additive Model
GBIF	Global Biodiversity Information Facility
GBM	Generalised Boosting Model
GCF	Giraffe Conservation Foundation
GCM	General Circulation Model
gHM	Global human modification of terrestrial land
GLM	Generalised Linear Model
GMPA	Government-Managed Protected Area
GSAT	Global Surface Air Temperature

GSD	Giraffe Skin Disease
ICCA	Indigenous and Community Conserved Areas
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
KAZA TFCA	Kavango-Zambezi Transfrontier Conservation Area
LCCS	Land Cover Classification System
Maxent	Maximum Entropy
MCM	Maximum Consecutive Months
MLR	Marginal Loss Rule
MNRT	Tanzania Ministry of Natural Resources and Tourism
NP	National Park
PA	Protected Area
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
ROC	Receiver Operating Characteristic
SDM	Species Distribution Model
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standardised Precipitation Index
SSP	Shared Socioeconomic Pathway
SSA	Sub-Saharan Africa
TAWIRI	Tanzania Wildlife Research Institute

TSS	True Skill Statistic
UN	United Nations
WDPA	World Database on Protected Areas



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Introduction

Giraffe are flagship species and considered highly charismatic, yet they are facing what experts have termed a 'silent extinction' (Albert *et al.*, 2018; Giraffe Conservation Foundation, 2016). Classed as one species with nine subspecies by the IUCN, in 2016 their threat status was changed from least concern to vulnerable due to the 36-40% population decline experienced from 1985-2015 (Muller *et al.*, 2018). However, the latest genetic and genomic research shows that giraffe are actually four different species with seven subspecies (Coimbra *et al.*, 2021). Recent estimates put the total number of giraffe in the wild at ~117,000 individuals, with some subspecies having as few as 600 individuals (Brown *et al.*, 2021). The main cause for declining giraffe populations is habitat loss, as well as poaching, civil unrest and ecological changes (Muller *et al.*, 2018).

Where species populations are already declining, future impacts from climate change could exacerbate this through changes in climate suitability; habitat loss caused by agricultural expansion due to changing climate suitability for crops; changes in extreme climate and weather events such as drought, flooding and fires; and changes to the distribution and abundance of both predators and food. Previous research has potentially underestimated the vulnerability of giraffe to climate change by modelling them as a single species, and failing to account for the complexities of climate change impacts and interactions with changing anthropogenic pressures. This thesis aims to better understand how climate change could impact each species and subspecies of giraffe under multiple global warming scenarios, to support the development of climate-resilient conservation actions both now and in the future.

The thesis consists of six further chapters and is structured as follows:

- Chapter 2 – A review of the literature on climate change and other, non-climatic factors impacting species' survival and giraffe as a study species, followed by a discussion of existing research on climate change impacts on giraffe and the remaining knowledge gaps.
- Chapter 3 – An assessment of observed and projected climate within the current geographic range of giraffe.
- Chapter 4 – The development of species distribution models to identify areas of observed and projected suitable climate.
- Chapter 5 – An analysis of priority areas for the conservation of each (sub)species of giraffe given both climatic and non-climatic threats.
- Chapter 6 – The introduction and brief overview of a web-based application for users to examine the outputs from this thesis.
- Chapter 7 – A synthesis and discussion of the implications of this research for the conservation of each (sub)species of giraffe, including conclusions and future research suggestions.

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Literature Review

This literature review covers five broad topics. First, projections of climate change are discussed alongside the impact that it has had or is projected to have on species. Next, non-climatic threats to species are discussed, followed by an introduction to giraffe as a study species – their distribution, diet, threats, and an overview of conservation plans. The final section identifies the research and knowledge gaps and specifies the aims of this thesis.

2.1 Climate change impacts on biodiversity

Climate change is a large threat to many species and has already been named as the prime cause of extinction in the Golden toad (*Incilius periglenes*) and Bramble Cay Melomys (*Melomys rubicola*) (Parmesan *et al.*, 2022). Projections under various global warming scenarios estimate that the percentage of species at very high risk of extinction globally (those projected to lose more than 80% of their climatically suitable range area) is 9% at 1.5°C, 10% at 2°C, 12% at 3.0°C, and 13% at 4°C (Parmesan *et al.*, 2022). Pollinators, Amphibians, and flowering plants are particularly at risk for global warming levels above 2°C (Warren *et al.*, 2018). Projections of local biodiversity loss indicate that South America, southern Africa, and Australia could see the largest declines (Parmesan *et al.*, 2022). Extinction risks are likely to differ depending on the region, with areas that have more endemic species with small ranges facing higher levels of extinction (Manes *et al.*, 2021; Urban, 2015). The vulnerability of a species to climate change is generally thought to be determined by their exposure to climatic change, their sensitivity to those changes, and

their adaptive capacity (Foden *et al.*, 2013; Williams *et al.*, 2008). A lack of dispersal ability and specialised habitat or food requirements are among the traits thought to make species particularly vulnerable to climate change (Pacifi *et al.*, 2015). There are nonetheless multiple ways in which research has attempted to quantify species' vulnerability, each with their own strengths, weaknesses and ranges of uncertainty (Pacifi *et al.*, 2015).

2.1.1 Geographic range changes

Species exist in areas suited to their physiological tolerances, but as the climate changes they are likely to follow the climate shift and move to areas that remain within their climatic tolerances (Parmesan, 2006; Root *et al.*, 2003). Commonly, this means that species will move poleward and to higher elevations (Hughes, 2000; Walther *et al.*, 2002). These range shifts can happen at multiple scales – either large scale shifts via dispersal, or smaller scale shifts in local- and micro-habitats (Bellard *et al.*, 2012). They can also happen both gradually and suddenly; for example, El Nino events may cause rapid range changes due to increased temperatures (Walther *et al.*, 2002). Range changes in response to climate change are not new; fossil records show that plants and animals have previously shifted their ranges in periods of changing climates (Blois and Hadly, 2009; Grayson, 2006; Jackson and Overpeck, 2000; Terry *et al.*, 2011). A meta-analysis by Parmesan and Yohe (2003) found that, on average, species range limits had moved 6.1 km northward or 6.1 m to higher altitude per decade. Chen *et al.* (2011) found similar results in their meta-analysis, with a median rate of 16.9 km per decade to higher latitudes and 11 m per decade to higher elevations. The rate of change has, however, been found to differ significantly between taxa (Mason *et al.*, 2015).

Climate induced range changes can be affected by, and potentially constrained by, various factors, such as dispersal ability and resource availability (Parmesan, 2006). Human activities causing habitat loss or fragmentation can reduce the ability of species to track changing climates, especially when combined with an already limited dispersal ability (Lenoir *et al.*, 2020). Additionally, if species track changing climates to areas which are otherwise not suitable for them, this may result in a reduction of range size and population (Forero-Medina *et al.*, 2011). Species at lower altitudes are particularly susceptible to this as more of the surrounding areas are suitable for human use (Forero-Medina *et al.*, 2011).

Many species will likely experience range loss due to climate change, with some groups being more susceptible than others. Under a 2°C warming scenario, Warren *et al.* (2018) found that 18% of insects modelled were projected to lose more than 50% of their geographic range, whilst this was only the case for 8% of the modelled vertebrates. If global warming is limited to 1.5°C instead of 2°C, Warren *et al.* (2018) found that this would reduce the amount of insects losing more than half of their range by ~66%, and by ~50% for plants and vertebrates.

2.1.2 Phenological and behavioural changes

Given that species' natural history traits can be highly reliant on, or triggered by, climatic cues, phenological changes are likely to happen, and have already been observed, as a result of climate change (Root *et al.*, 2003). This can include changes in the timing of seasonal migrations, breeding, nesting, spawning, budding, shooting, flowering, and fruiting (Bellard *et al.* 2012; Parmesan and Yohe, 2003; Walther *et al.*, 2002). Early meta-analyses, such as Root *et al.* (2003), found evidence of spring phenological shifts at an average of 5.1 days earlier per decade. More recently, in a review of in-situ observations of plants, Piao *et al.* (2019) found that the average advancement in days per decade was 5.5 in China, 4.2 in Europe, and 0.9 in North America. Although earlier Spring timings have mostly been documented, there is some evidence for changes in the timing of Autumnal events (Gallinat *et al.*, 2015; Walther *et al.* 2002).

Phenological responses to climate change are not necessarily uniform between species and can potentially be affected by additional factors. Thackeray *et al.* (2016) suggest that differences in phenological responses within regions may be due to differences in population structure, resource availability, and adaptation. It has been suggested that phenological changes in breeding for birds may differ due to diet, body size, local temperature changes, and life history traits (Dunn, 2004). Cohen *et al.* (2018) also found that body size, as well as phylogeny, was associated with differences in phenological changes in animals. Ovaskainen *et al.* (2013) found that phenologies of birds and insects were mainly dependent on short-term climatic cues, whilst for plants, herptiles and fungi, longer-term climatic averages were more important. The main drivers of phenological changes can also differ latitudinally. Temperature seems to be the main driver at

mid-latitudes, whilst precipitation seems to be the main driver at lower latitudes (Cohen *et al.*, 2018).

2.1.3 Biotic interactions

Changes in distribution and phenology can in turn affect interactions between species, for example, in terms of predation, competition, and herbivory (Hughes, 2000; Walther *et al.*, 2002). When considering multiple trophic levels or taxonomies, it is possible that species will have varying responses to climate change and that their phenologies will not shift at the same rate, causing phenotypic mis-timings (Ovaskainen *et al.*, 2013; Visser *et al.*, 2004). This has already been observed in some species (Van Asch *et al.*, 2007; Visser and Holleman, 2001). A meta-analysis by Kharouba *et al.* (2018), found that a majority of directly interacting species were experiencing shifts which bring the timing of phenotypic events closer together. However, 43% of directly interacting species were experiencing shifts resulting in the timing of phenological events being further apart. Where there is evidence for body size being associated with differing phenological responses or rates of change, Cohen *et al.* (2018) suggest that this may be particularly important for mutualistic, predator–prey, and host–parasite interactions where these species typically vary in body size.

2.1.4 Physiology and Morphology

Changes in temperature, precipitation and CO₂ levels may affect species' physiology (Hughes, 2000). In animals, this may be in terms of their metabolism and development, whilst for plants it may affect photosynthesis, respiration, protein availability, and growth. Some documented cases of the effect of climate change on physiology include increased heat tolerance in *Anolis* lizards (Deery *et al.* 2021), changing reproductive rates in aquatic species (Kirby *et al.* 2006), and changing determinants of sex in lizards (Telemeco *et al.* 2009). In some species, plasticity in thermal tolerance may enable them to survive increasing temperatures, however there is evidence that species with high upper thermal limits may be at risk due to the associated increased metabolic costs of living under sustained increasing temperatures (Magozzi and Calosi, 2015).

Some species have already undergone climate-induced morphological changes, including

changes in body size and colour. A reduction in body size is largely expected under increasing temperatures as it would maximise heat loss (Parmesan *et al.*, 2022). This has already been observed in birds, mammals, fish, terrestrial ectotherms, and plants (Sheridan and Bickford, 2011). Changes to body size are likely due to climate change through, for example, phenological shifts causing longer growing seasons or warming temperatures improving food resources (see Ozgul *et al.*, 2010; Yom-Tov *et al.*, 2008). It has also been noted that many examples of increasing body size due to climate change are from high latitudes where climate change is increasing net primary productivity (Sheridan and Bickford, 2011).

2.1.5 Climate change projections

Future climate change is expected to alter temperature regimes, precipitation patterns, and the frequency and intensity of extreme events at both global and regional scales. These changes provide the broader climatic context within which potential impacts on giraffe populations can be considered. This section summarises projected changes in climate at global and Sub-Saharan African scales.

Projections of climate change are often discussed in the context of representative concentration pathways (RCPs), which represent the level of radiative forcing (in watts per square metre, or W/m^2) resulting in the year 2100 for the given scenario. In the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), a new set of Shared Socioeconomic Pathway (SSP) based scenarios (SSPx-y) were defined for assessing future climate change (Chen *et al.*, 2021). In these scenarios, the ‘SSP[1-5]’, details the socioeconomic trends underlying the scenario, and ‘y’ is the radiative forcing at 2100. Importantly, whilst similar, these SSPx-y scenarios are not directly comparable with standalone RCP scenarios due to slight differences in gas-to-gas composition, emissions trajectories, and overall effective radiative forcing (Chen *et al.*, 2021).

Temperature and precipitation

The latest IPCC report shows projected surface air temperatures for short (2021-2040), mid (2041-2060), and long (2081-2100) term timescales under different SSPx-y scenarios (Lee *et al.*, 2021). Relative to 1850-1900, an increase of 1.5°C in global annual mean surface air temperature (GSAT) is at least more likely to occur than not under all scenarios in the 2021-

2040 timeframe. In the 2041-2080 timeframe, 2°C is crossed in three of the scenarios, and by 2081-2100, 3°C is crossed in two scenarios (Table 2.2). At 1.5°C of global warming, models project increases in land precipitation of 1.5-2% depending on the SSPx-y scenario (Lee *et al.*, 2021). At 2°C of warming, this increases to 3.8% for SSP1-1.9, 2.2% for SSP1-2.6, 2.8% for SSP2-4.5 and SSP5-8.5, and 2.4% for SSP3-7.0. For scenarios where 3°C of warming is reached, model averages show a 4.3-4.9% increase in land precipitation. The IPCC report also concludes that, regardless of the SSPx-y scenario, global mean sea level is projected to continue to rise over the century (Lee *et al.*, 2021).

Table 2.1: 20-year averaged global surface air temperature (GSAT) change for each SSPx-y and timeframe, relative to 1850–1900. Adapted from Table 4.5 in Lee *et al.* (2021, p. 582). Values show the central estimate, and 5-95% range in parentheses.

Time Period	SSP1-1.9 (°C)	SSP1-2.6 (°C)	SSP2-4.5 (°C)	SSP3-7.0 (°C)	SSP5-8.5 (°C)
2021-2040	1.5 (1.2, 1.7)	1.5 (1.2, 1.8)	1.5 (1.2, 1.8)	1.5 (1.2, 1.8)	1.6 (1.3, 1.9)
2041-2060	1.6 (1.2, 2.0)	1.7 (1.3, 2.2)	2.0 (1.6, 2.5)	2.1 (1.7, 2.6)	2.4 (1.9, 3.0)
2081-2100	1.4 (1.0, 1.8)	1.8 (1.3, 2.4)	2.7 (2.1, 3.5)	3.6 (2.8, 4.6)	4.4 (3.3, 5.7)

Sub-Saharan Africa:

In the IPCC AR6 report, Sub-Saharan Africa (SSA) is usually divided into several reference regions: Western Africa (WAF), Central Africa (CAF), North Eastern Africa (NEAF), South Eastern Africa (SEAF), West Southern Africa (WSAF), East Southern Africa (ESAF). Temperatures across SSA are projected to increase under all emissions scenarios, with mean temperatures increasing with every increase in global warming (see Figure 2.1). Depending on the region, by 2050 temperatures are projected to increase in the range of 0.5°C – 2.5°C under all scenarios (Ranasinghe *et al.*, 2021). Under SSP1-2.6, the mean annual temperature increase across Africa is 1.2°C for 2030-2059, and 1.4°C for 2070-2099 (Almazroui *et al.*, 2020). Projections of changes to mean precipitation vary across SSA, both spatially and seasonally, and there are some disagreements between global and regional model ensembles (Dosio *et al.*, 2021). The IPCC report states a medium and high confidence of precipitation decreases in ESAF and WSAF, respectively, by 2100 (Ranasinghe *et al.*, 2021). In WAF, mean precipitation is projected to increase across eastern portions and decrease in western portions. Dosio *et al.* (2021) found that mean ensembles of

regional and global climate models (CMIP6, CMIP5, CORDEX-Africa, CORE) under SSP1-26, SSP2-45, and SSP5-85 up to 2100, all project decreases in the number of rainy days (days with >1 mm precipitation) for the June-August season in western Sahel, and in the December-February season in east Africa, southern central Africa, and southern Africa. Over the Horn of Africa, the majority of models in each ensemble projected an increase in the number of rainy days in the September-November season.

Overall, climate models consistently project widespread warming across all regions of Sub-Saharan Africa, with varying signals of precipitation change. Southern Africa is generally expected to become warmer and drier; eastern Africa is projected to become warmer, but experience increases in rainfall in some seasons; and West Africa shows mixed patterns of increasing and decreasing precipitation, depending on the location.

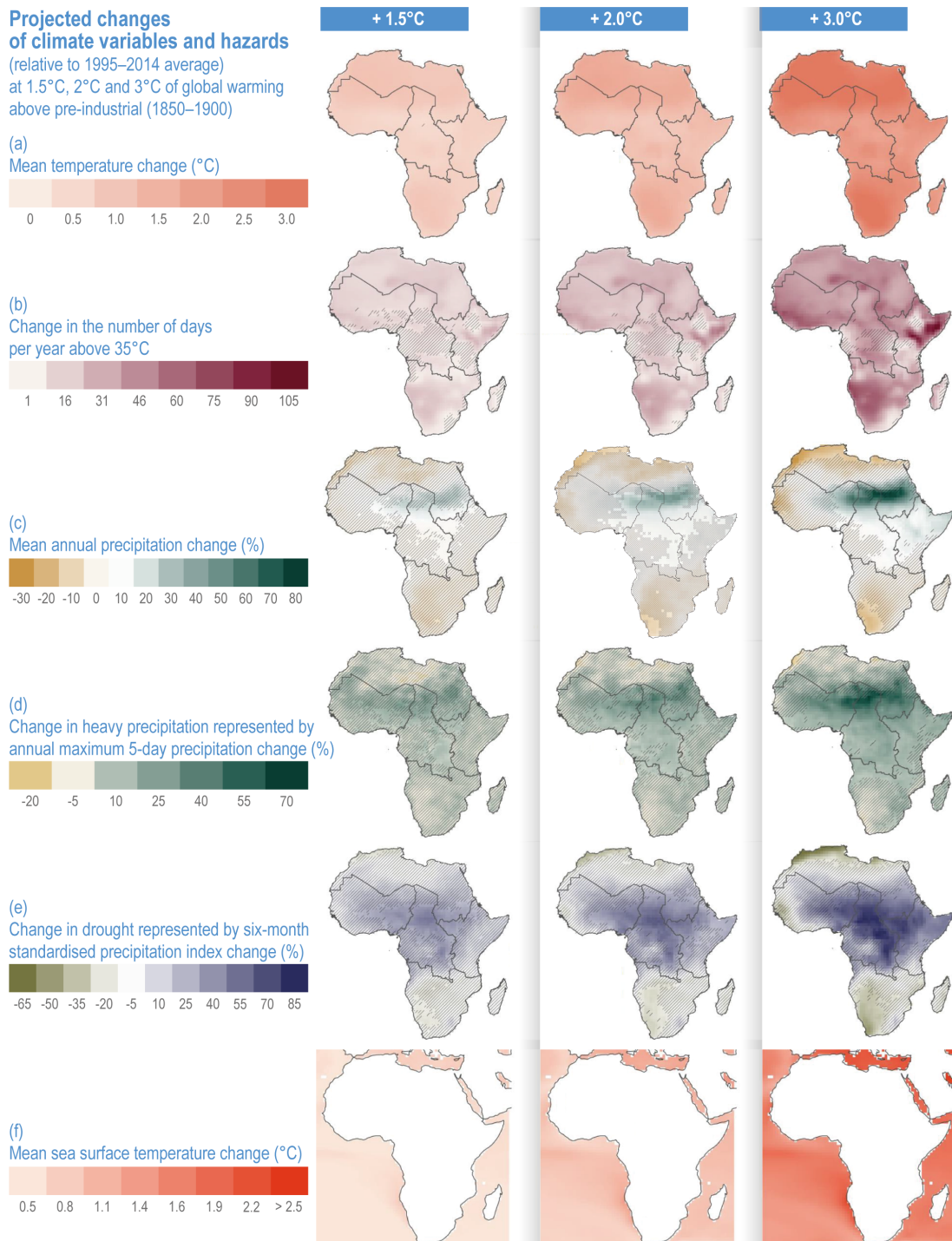


Figure 2.1: Projections of climate change over Africa from between 26 - 33 CMIP6 (Coupled Model Intercomparison Project) models, relative to the 1995-2014 average, at 1.5°C, 2°C, and 3°C global warming relative to pre-industrial levels (1850-1900). From top to bottom: (a) Mean temperature change (°C); (b) Change in the number of days per year above 35°C (days); (c) Mean annual rainfall change (%); (d) Heavy (annual maximum 5-day) precipitation change (%); (e) Change in drought represented by the six-month standardised precipitation index (SPI) (%) – negative values show projected increases in drought frequency, intensity and/or duration and positive values show decreases; and (f) Mean sea surface temperature change (°C). Model agreement in the projected change signal is indicated by hatching – diagonal lines (/) indicate areas with fewer than 80% of models agreeing on the sign of change. Figure from Trisos *et al.* (2022, Figure 9.16, p. 1324)

Extreme events

As well as changes in average climate conditions, global warming is projected to cause an increase in the frequency and intensity of extreme weather events and extreme climatic events (ECEs). The IPCC defines extreme weather as ‘an event that is rare at a particular place and time of year’, and an ECE as ‘a pattern of extreme weather that persists for some time, such as a season’ (Seneviratne *et al.*, 2021b, p. 1522). This encompasses extreme temperature and precipitation events, droughts, floods, storms, and heatwaves, which can also occur simultaneously or in quick succession to cause events such as fires.

Global projections of extreme hot temperatures and extreme precipitation show an increasing frequency and severity under global warming, whilst cold temperature extremes are projected to become less frequent and intense (Li *et al.*, 2021). Globally, an increase from 1°C to 2°C of warming could see around five times more 1 in 50-year hot temperature events (Li *et al.*, 2021). The magnitude, extent and duration of heatwaves is projected to increase across different warming levels (Vogel *et al.*, 2020). Extreme precipitation events are projected to increase with higher warming levels for most of the global land area (Seneviratne *et al.*, 2021b). From 1°C to 2°C of warming, 1 in 50-year maximum precipitation events are projected to become ~1.5 times more likely and around 6-7% more intense (Li *et al.*, 2021). There is also projected to be an increase in the frequency of extreme flood events and global flood risk with global warming (Alfieri *et al.*, 2017; Paltan *et al.*, 2018, p. 5).

Increasing levels of warming, even at increments of 0.5°C, are projected to cause increases in the duration, frequency and intensity of meteorological, agricultural, ecological, and hydrological droughts in at least some regions (Seneviratne *et al.*, 2021b). For example, meteorological droughts – those based on precipitation deficits – are projected to become longer and more frequent in the subtropics, more intense in the tropics, and shorter but more intense in the mid-high northern latitudes (Ukkola *et al.*, 2020). More regions are projected to see increases rather than decreases in agricultural and ecological droughts under increasing warming levels (Seneviratne *et al.*, 2021b).

Sub-Saharan Africa:

Across SSA, extreme high temperature events (e.g. heatwaves, warm days), particularly 1

in 50-year events, are projected to increase in severity and frequency at increasing global warming levels (Li *et al.*, 2021; Seneviratne *et al.*, 2021b). Conversely, cold extremes are projected to decrease in severity and frequency across Africa. By 2100, the number of days per year exceeding 35°C is projected to increase under SSP1-2.6 by 40-50 days in WAF, ESAF, WSAF, and NEAF (Ranasinghe *et al.*, 2021).

Extreme precipitation events are projected to increase across most of Africa (see Figure 2.1; Seneviratne *et al.*, 2021a), with daily precipitation extremes increasing more under higher warming levels. Projected increases in heavy precipitation are modelled for Southern Africa, WAF, CAF, and Eastern Africa. In NEAF and CAF, projections show an increase in extreme precipitation intensity, but with seasonal differences in trends (Dosio *et al.*, 2019). Projections show that WSAF could see a decrease in heavy precipitation (Pinto *et al.*, 2018). Whilst extreme flooding events can be difficult to project, pluvial and urban floods can be inferred from projections of heavy precipitation, because they are caused by the volume of precipitation exceeding natural and urban drainage systems capacity. River flooding, however, is more complex and hydrological models projecting streamflow (used as a proxy for flooding) are highly uncertain, often with large biases (Seneviratne *et al.*, 2021a).

Projections of changes to drought conditions show increases in the duration of meteorological drought across southern and western Africa and increases in drought intensity across parts of southern Africa (Ukkola *et al.*, 2020). For agricultural and ecological drought, the IPCC AR6 report states a high confidence of increase across WSAF and a medium confidence of increase in ESAF (for global warming levels of between 2-2.4°C mid-century; Ranasinghe *et al.*, 2021). In WAF, SEAF, and NEAF, there is a contrasting regional signal, showing drying in western portions and wetting in eastern portions.

Overall, climate projections for Sub-Saharan Africa show a strong increase in temperature extremes across all regions, with heatwaves and extreme high temperature events projected to increase in frequency and severity across the continent. In contrast, projections of precipitation extremes and drought differ regionally: southern and western Africa are projected to experience more frequent and severe drought, while eastern and central Africa are more likely to see increases in heavy precipitation, with substantial seasonal variability.

2.2 Non-climatic factors affecting species

2.2.1 Human population growth

Human population growth is considered a threat to species due to the associated threats of increased habitat loss, poaching, and the introduction of invasive species (Cardillo *et al.*, 2004). Despite this, some research has shown that species richness can be positively correlated with human population density (Araújo, 2003; Balmford *et al.* 2001; Cincotta *et al.*, 2000; Gallant *et al.*, 2007; Luck, 2007). Human population growth and density have been linked to species extinction risk at both local and regional scales (Harcourt and Parks, 2003; McKee *et al.*, 2004). Some estimates point to an increase in the number of threatened species globally of ~15% by 2050, due to population growth (McKee *et al.*, 2004). Barnes (1990) found that human population size, not density, was one of the most important factors in determining the absolute area deforested in an African rainforest, whilst population density explained ~20% of the variation in the percentage of area felled. Harcourt *et al.* (2001) found that human population density around several reserves in Africa was correlated with human-induced mortality, but in general, the size of the reserve was a better predictor of ungulate and carnivore extirpation. A similar study found that 98% of the variation in the local extinction rate within African reserves was accounted for by nearby human population size and reserve size, with larger human population and smaller reserve size having higher extinction rates of large mammals. (Brashares *et al.*, 2001). In the United States of America, extinction rates of large mammals within National Parks were significantly correlated with higher local human population density, but not reserve area (Parks and Harcourt, 2002).

2.2.2 Habitat loss, land use and land cover change

Habitat loss is often cited as the biggest threat to biodiversity, along with habitat fragmentation. Species with smaller ranges are more likely to go locally extinct due to habitat loss (Staude *et al.*, 2020), although the reaction of a species to habitat fragmentation depends on their life history traits and dispersal ability (With and King, 1999).

Human induced land use and land cover (LULC) change are prime causes of habitat loss and fragmentation. The IPBES Global Assessment Report on biodiversity and ecosystem

services states that, globally, 'land-use change has had the largest relative negative impact on [terrestrial and freshwater ecosystems] since 1970' (IPBES, 2019, p. XVI). It can affect species composition (Newbold *et al.*, 2016) and species richness (Murphy and Romanuk, 2014; Waltert *et al.*, 2004). Conversion of species' habitat into urban or agricultural land is considered the most important land-use change with respect to the impact on biodiversity (de Chazal and Rounsevell, 2009). Protected areas can be effective in preventing habitat loss, but land-use change outside of these areas can still affect species within them through changes in source-sink population dynamics (Hansen and Rotella, 2002). Changes in the management of land can also affect biodiversity, both positively and negatively, and at varying scales (Haines-Young, 2009). As of 2019, agricultural land covered ~4.8 billion hectares, or around a third of total land surface (FAO, 2022), and over the last 150 years, agricultural practices have largely intensified (Zeller *et al.*, 2017). When comparing an adjacent area of lightly grazed government-owned land with a heavily grazed communal patch of land, Hoffmann and Zeller (2005) found that species richness and abundance was lower in the highly grazed area. This reduction in species richness is accompanied by a loss of functional diversity under higher land use intensities (Flynn *et al.*, 2009).

Land Use and Land Cover (LULC) is driven by both anthropogenic and environmental factors, with complex feedback loops between the two. The effects of climate change on LULC includes shifts in agricultural land due to changing climatic suitability for crops, changes in vegetation cover due to increasing CO₂ fertilisation, sea level changes affecting coastal areas, and land clearance and disturbance from increased drought and fire frequency (Shukla *et al.*, 2019). Projections of land use in Africa, for example, show a general increase in cropland, grassland and urban land, but a decrease in forest land by 2100 (Yahaya *et al.*, 2024).

A key consequence of climate change is the projected reduction in the yields of many important crops (Rosenzweig *et al.*, 2014), which may in turn drive agricultural expansion. Zhao *et al.* (2017) found that, globally, each degree-Celsius temperature increase is projected to cause yields of wheat to reduce by 6%, rice by 3.2%, maize by 7.4% and soybean by 3.1%. In terms of LULC, Jantz *et al.* (2015) found that, under a range of RCPs, crop expansion would account for 2-20% of loss of natural vegetative cover in biodiversity hotspot areas, whilst pasture expansion would account for 1-10%. Similarly, von Lampe *et*

al. (2014) suggest that up to 26% more land could be used for five key crops by 2050, depending on the climate change scenario and model used.

These land-use projections are informative but also contain high uncertainties due to the difficulty in projecting complex socio-economic factors, such as shifts in policy, agricultural practices, and afforestation or habitat restoration projects (Dale, 1997; Popp *et al.*, 2017; Albert *et al.*, 2020). For example, at a more local scale, one assessment of farmers' land management preferences under future drought scenarios and without water-policy interventions, varied from maintaining their current farming practices (28%), keeping their crops but reducing the amount of area used (24%), or abandoning their farming practice (18%) (Yang *et al.*, 2016).

2.2.3 Disease

Disease can be responsible for large reductions in species population size as well as local extinctions (see Roelke-Parker *et al.*, 1996), but it is not often the cause of total species extinction (Heard *et al.* 2013). Even within the same species, susceptibility to a disease may differ between populations and individuals due to factors such as genetic uniformity, group size, age, sex, and reproductive status (Müller-Graf *et al.*, 1999).

Disease can be spread by spill-overs from reservoir hosts (those that are normally found to have the disease) to other wildlife found in the same place at the same time (Daszak *et al.*, 2000). The rinderpest outbreak in Africa in the late 1800s was due to a spillover from cattle to other species, the most susceptible of which were buffaloes, giraffe, wild suids and spiral-horned antelopes (Barrett and Rossiter, 1999). During this outbreak, 90% of Kenya's buffalo population died and the tsetse fly went locally extinct (Barrett and Rossiter, 1999; Daszak *et al.*, 2000). Similarly, human population expansion can cause 'pathogen pollution' – the introduction of exotic pathogens by humans (Daszak *et al.*, 2000). One theory for the population decline and subsequent extirpation of wild dogs in the Serengeti National Park in the 1990s is that increasing human populations near to the Serengeti borders lead to spillover from domestic dogs (Ginsberg *et al.*, 1995). There is also a concern that when implementing translocations of animals under conservation strategies, diseases may be spread to new areas where resident species are susceptible (Sainsbury and Vaughan-Higgins, 2012; Woodford, 1993).

Climate change increases disease risk through several mechanisms, including changes to pathogen and host geographic ranges; more favourable climate conditions for transmission and exposure; and changes to pathogen and host survival, growth and development (Parmesan *et al.* 2022). Following the thermal mismatch hypothesis, species adapted to cool climates will likely experience higher disease risk with uncharacteristically warm temperatures, whilst the opposite is true for species in warm climates (Cohen *et al.*, 2017). Parasites and hosts are assumed to be locally adapted to their climates, but due to the generally broader thermal tolerance of parasites, under unusual climatic conditions, parasites will likely have an advantage over their hosts. This has shown to be true under laboratory conditions (Cohen *et al.* 2017) and is a likely cause of the decline of several species observed in the field (Cohen *et al.*, 2019). Further investigation by Cohen *et al.* (2020) revealed that ectothermic and non-migratory hosts are most affected by thermal mismatch, and that terrestrial and freshwater systems see largely similar effects. Climatic extremes such as drought have also been documented to precede fatal co-infection events in lions, where diseases that do not usually cause high levels of mortality occurred simultaneously with parasite infestations (Munson *et al.* 2008).

2.2.4 Predation and food limitation

Predation and food limitation can largely affect species populations; predation is a 'top-down' pressure, whilst food limitation is a 'bottom-up' pressure. Predators affect prey species' populations through direct predation pressure and their influence on anti-predator and risk-taking behaviours (Creel and Christianson, 2008; Lima, 1998). 'Keystone predators' largely control the community structure and can affect prey distribution and abundance (Menge *et al.*, 1994). A meta-analysis of 116 predator manipulation experiments showed that vertebrate predators do limit prey populations (Salo *et al.*, 2010), and the removal of predators can cause a ~1.5-fold increase in prey population sizes (Holt *et al.*, 2008; Salo *et al.*, 2010). The effect of predation is further complicated when a species has multiple predators, or depending on whether a species is a primary or secondary prey item (Pech *et al.*, 1995; Sih *et al.*, 1998).

Food supply is largely responsible for the population growth rate of a species (Sinclair and Krebs, 2002). Larger species are less vulnerable to predation, and as such, food supply is

usually the main factor regulating these populations (Sinclair, 2003). Mduma *et al.* (1999) found that food supply was the main limiting factor in a wildebeest population over a 40-year period, with dry-season rainfall being the primary determinant of food availability. Similarly, food availability was thought to be the main limiting factor of population size in a reintroduced population of bison (Larter *et al.*, 2000). The interaction between predation and food limitation can also affect species populations. As species forage, their strategy usually reflects an element of predator awareness, through avoidance of habitats and risk-taking behaviours. As the need for food increases, species will increase the risk they are willing to take to access the food resources (McNamara and Houston, 1987).

2.3 Giraffe as a study species

Giraffe (*Giraffa* spp.) were chosen as the focal species for this research for several reasons. Over the last half century, giraffe populations have experienced substantial declines and increasingly fragmented ranges, raising concerns about their conservation. This vulnerability has been further highlighted by the recent reclassification of giraffe from a single species into four genetically distinct species, with more restricted distributions and differing conservation statuses. Together, these factors suggest that giraffe may be more vulnerable than previously assumed to both direct and indirect impacts of climate change, and any concurrent non-climatic threats, making them an appropriate study species for this research.

2.3.1 Brief Morphology, physiology, and life history

Giraffe are perhaps most well known for their long necks and distinct pelage patterns (Mitchell, 2021a). Classed as megaherbivores, female and male giraffe weigh about 800 kg and 1200 kg, respectively, and can grow up to 5.5 m tall (Dagg, 1971; Bertelsen, 2015; Dagg and Foster, 1976; Warren, 1974). Giraffe are well adapted to warm climates (Mitchell and Skinner, 2004); they are dolichomorphic in shape, aiding in their ability to thermoregulate (Brownlee, 1963; Mitchell *et al.*, 2017). This likely improves their rate of heat loss through convection and evaporation, the latter being the giraffe's main physiological mechanism for cooling down (Mitchell *et al.*, 2018, 2017; Mitchell and Skinner, 2004). The average body temperature of a giraffe is around 38.5°C (Bligh and Harthoorn, 1965; and see Mitchell and

Skinner, 2004). A study by Dagg in 1970 (as cited by Mitchell and Skinner, 2004) found that giraffe seek shade for extreme ambient temperatures such as those above 50°C, and a study by Langman and Maloiy (1989) found that giraffe seek shade or try to reduce the amount of their body exposed to the sun if their body temperature reaches 40°C. There is some evidence that the patterned coat of giraffe plays a role in thermoregulation, but more research is needed to confirm this (Mouchet *et al.*, 2025).

Giraffe are widely assumed to live for no longer than 30 years, with a generation length of ~10 years (Muller *et al.*, 2018a; Suraud *et al.*, 2012). Although females have been noted to live longer than males, who are thought to have a maximum lifespan of 22 years, the average life expectancy for females is not significantly more than that of males (at ~17 years and 14 - 16 years, respectively) (Berry and Bercovitch, 2012; Bercovitch and Berry, 2017). Giraffe calves are born all year round (Sinclair, 1995). Estimates of giraffe birth rates suggest that giraffe have one calf around every 22 months (Shorrocks, 2016), although this interval fluctuates slightly with different populations, including between captive and wild giraffe (Foster and Dagg, 1972; Hall-Martin and Skinner, 1978; Pellew, 1983). Around 50% of giraffe calves die before one year of age (Pellew, 1983; Lee *et al.*, 2016a), with estimates of calf survival in the literature ranging from 23% to 57% (Foster and Dagg, 1972; Sinclair, 1995; Strauss *et al.*, 2015).

These physiological and life-history traits suggest that giraffe are relatively well adapted to warm environments, particularly in terms of heat dissipation and behavioural thermoregulation. However, this does not imply resilience to ongoing climate change, as further increases in temperature may push individuals closer to thermal tolerance limits or affect giraffe indirectly through changes in forage availability and water resources. In addition, the long generation times, low reproductive rates, and high calf mortality of giraffe may constrain the speed at which populations can respond demographically to rapid environmental change. Consequently, while adult giraffe may persist under higher temperatures, long-term population viability under climate change is likely to depend on the spatial availability of suitable habitat and climate refugia rather than rapid evolutionary or demographic adaptation.

2.3.2 Taxonomy

Giraffe and okapi, both endemic to Africa, are the only members of the family Giraffidae. Differences in pelage colour, morphology and distribution have meant that the number of giraffe species has long been subject to debate (Lydekker, 1904; Brown *et al.*, 2007; Fennessy *et al.*, 2017; Bercovitch *et al.*, 2017). Early research suggested that there could be two species, but estimates have ranged from one species to six or more species, with various numbers of subspecies (Lydekker, 1904; Dagg, 1971; Brown *et al.*, 2007; Groves and Grubb, 2011; Dagg, 2014a; Fennessy *et al.*, 2016; Petzold *et al.*, 2020; Coimbra *et al.*, 2021). The most recent IUCN assessment, published in 2018, recognises one species and nine subspecies, based on Dagg (1971), but also acknowledges that ‘a future reassessment might be in order’ and that it would be ‘premature to alter the taxonomic status quo’ until this is done (Muller *et al.* 2018a). Since this assessment, work published by Fennessy *et al.* (2016) and Coimbra *et al.* (2021) has shown through genetic and genomic data that several genetically distinct lineages of giraffe have been evolving separately for 230–370 thousand years. This led the authors to suggest a taxonomy of four species and seven subspecies of giraffe (Table 2.2), although this is not a general consensus amongst researchers in the field (see Bercovitch *et al.*, 2017). Some critics of the four species taxonomy argued that Fennessy *et al.* (2016) did not complete a comprehensive gene-flow analysis, but the subsequent study by Winter *et al.* (2018) further examined gene flow and found evidence to support the four-species taxonomy. More recently, research using multiple methods of multi-locus DNA sequence analysis found no support for a one-species taxonomy and instead identified between 2-6 species of giraffe (Petzold and Hassanin, 2020).

Species taxonomy has important implications for conservation practices in terms of management, translocations, and recognised threatened status (Muneza *et al.*, 2025). For example, splitting a wide-ranging species into multiple, range-restricted species would likely result in the newly recognised species being categorised under a higher threatened status (Agapow *et al.*, 2004; Isaac *et al.*, 2004; Mace, 2004). Where translocations are used as a conservation strategy, changes to taxonomy also influence which populations can serve as appropriate sources, as practitioners aim to avoid outbreeding risks and preserve locally adapted genetic lineages (Frankham *et al.*, 2011).

Taxonomy also has important implications for understanding the projected impacts of

climate change on giraffe. Treating giraffe as one species with a continent-wide distribution risks lumping together genetically and ecologically distinct taxa that have different climatic niches. This could lead to an overestimation of climatic niche breadth and a possible underestimation of species-specific exposure and vulnerability to climate change.

Given the weight of evidence against a one-species taxonomy for giraffe, and the growing consensus on a four-species taxonomy, this thesis henceforth adopts the four-species taxonomy, examining four species and seven subspecies of giraffe (Table 2.2). This distinction underpins the species-specific species distribution models developed in this thesis, allowing climate suitability, exposure, and potential climate refugia to be assessed at a biologically meaningful taxonomic scale.

Table 2.2: The species and subspecies of giraffe as first proposed by Fennessy *et al.* (2016).

Species	Subspecies
Northern giraffe (<i>Giraffa camelopardalis</i>)	Nubian giraffe (<i>G. c. camelopardalis</i>)
	West African giraffe (<i>G. c. peralta</i>)
	Kordofan giraffe (<i>G. c. antiquorum</i>)
Reticulated giraffe (<i>Giraffa reticulata</i>)	
Masai giraffe (<i>Giraffa tippelskirchi</i>)	Masai giraffe (<i>G. t. tippelskirchi</i>)
	Luangwa giraffe (<i>G. t. thornicrofti</i>)
Southern giraffe (<i>Giraffa giraffa</i>)	Angolan giraffe (<i>G. g. angolensis</i>)
	South African giraffe (<i>G. g. giraffa</i>)

2.3.3 Continental distribution and population trends

Giraffe occur across much of Sub-Saharan Africa, but most populations are highly fragmented (Shorrocks, 2016). The 2016 IUCN assessment states that giraffe are native to 18 countries, but recent research has found that they are currently present in 21 (Muller *et al.* 2018a; O’connor *et al.*, 2019). Since the IUCN assessment, giraffe ranges in individual countries have both increased and decreased. For example, the geographic range area of giraffe has increased in Kenya (for Reticulated giraffe), Botswana, Ethiopia, Mozambique, South Sudan, Tanzania and Zimbabwe; but decreased in Cameroon, Central African

Republic, Chad, Kenya (for Northern giraffe and Masai giraffe), Malawi, Niger, Uganda, and Zambia (O'Connor *et al.*, 2019). Overall, there has been a 5.6% decline in total geographic range area, with Northern giraffe experiencing the largest range decline of 37% (O'Connor *et al.* 2019). This overall reduction in range size is not surprising, as giraffe have notably experienced population declines in previous years (Muller *et al.*, 2018a; Pellew, 1983; Strauss *et al.*, 2015). The IUCN report showed that at the time of assessment, overall numbers of giraffe were declining (Muller *et al.*, 2018a). However, the population trends between the nine assessed subspecies were mixed: *G. c. angolensis*, *G. c. giraffa*, *G. c. peralta*, and *G. c. rothschildi* had increasing populations; *G. c. antiquorum*, *G. c. camelopardalis*, *G. c. reticulata*, and *G. c. tippelskirchi* had decreasing populations; and *G. c. thornicrofti* had a stable population (Muller *et al.* 2018a). An example of this trend in population decline is the Serengeti National Park, where estimates show giraffe populations had declined from ~10,750 in 1975-1977 to ~3,520 in 2008-2010 (Pellew, 1983; Strauss *et al.*, 2015).

Despite previous population declines, work by the Giraffe Conservation Foundation (GCF) has shown that as of 2021, the number of giraffe is now increasing, and the total number is estimated at ~117,000 (Brown *et al.*, 2021). This is an increase of around 20% since 2015, although this can be in part attributed to better, more accurate methods of estimating population numbers as well as actual population growth (Giraffe Conservation Foundation, 2021; Brown *et al.*, 2021; Muller *et al.*, 2018a). This trend of increasing population is seen across all four species of giraffe. From 2015 to 2020, Northern giraffe have increased from 4,776 to 5,919 individuals, Masai giraffe have increased from 31,611 to 45,402 individuals, Reticulated giraffe have increased from 8,661 to 15,985 (Brown *et al.*, 2021). Since 2015 Southern giraffe have decreased from 51,969 to 48,016 individuals (not including hybrid giraffe or extralimital giraffe), but the current population trend is increasing (Brown *et al.*, 2021). Even with population increases, West African giraffe still only number 600 individuals, making them the smallest population out of all species and subspecies (Brown *et al.*, 2021; Gašparová *et al.*, 2020).

Population growth can be affected by predation, poaching, disease, competition, resource availability, habitat loss, and environmental changes (Shorrocks, 2016). Important factors for population growth in giraffe include calf and adult survival, resource availability, and

social factors, such as time spent in groups (Bond *et al.*, 2021c; Pellew, 1983a; Strauss *et al.*, 2015). Pellew (1983) showed that population growth of giraffe populations in the Serengeti National Park was largely linked to food resource availability. A later study by Strauss *et al.* (2015) showed that population decline had been a product of fewer calves being born, as well as increased adult mortality. These factors were attributed to a drop in available food resources causing poor nutrition, and an increase in poaching in the area. It was suggested that population growth was influenced more by adult survival than calf survival, given that calf survival rates had actually increased in the area despite the population decline (Strauss *et al.*, 2015). Suraud *et al.* (2012) support this, noting that calf survival is only the main limiting factor of population growth when poaching of adults is prevented. Other studies have also pointed towards poaching as a cause of population decline in giraffe (Ogutu *et al.*, 2011).

The fragmented nature of many giraffe populations could increase their vulnerability to climate change by limiting their ability to shift geographic ranges and track areas of suitable climate. This is of particular concern for Northern giraffe, which have experienced the greatest historical range contraction. In addition, food availability is a key determinant of giraffe population growth, and climate-driven changes in vegetation productivity, phenology, or forage quality may further constrain population persistence, even where climatic conditions remain otherwise suitable.

2.3.4 Home range and habitat

The size and location of giraffe home ranges differs markedly between populations. The four species of giraffe can be found in varying types of habitat, including open savanna, woodland areas, shrubland, and grassland (Deacon and Tutchings, 2019; Hart *et al.*, 2020; Muller *et al.* 2018b). Mean home range size has been shown to vary from 5.2 – 513.9 km² for males, and 8.6 – 199.5 km² for females across different populations (Fennessy, 2009; van der Jeugd and Prins, 2000). These differences in home ranges can be at least partly explained by climate, habitat preference and accessibility, food and water availability, giraffe population density, topography, as well as distance from human settlements (Dagg and Foster, 1976; Deacon and Smit, 2017, 2017; Fennessy, 2009; Kimuyu *et al.*, 2021, 2021; Knüsel *et al.*, 2019; Waltert *et al.*, 2009).

Giraffe are non-territorial species (Brown *et al.*, 2007; van der Jeugd and Prins, 2000) and as such, their home ranges overlap both between sexes and populations (Deacon and Smit, 2017; Fennessy, 2009; Leuthold, 1979; van der Jeugd and Prins, 2000; Van der Waal *et al.*, 2013). One study in northern Tanzania found that, on average, the home range of one giraffe subpopulation would overlap with four others (Bond *et al.* 2021b). In areas of lower giraffe population density, home ranges tend to be larger (Fennessy, 2009), although this is not always the case (see Knüsel *et al.*, 2019). In many cases males have larger home ranges than females (Berry, 1978; Fennessy, 2009; Knüsel *et al.*, 2019). This is likely due to males moving further distances in search of fertile females (Bercovitch *et al.*, 2006; Fennessy, 2009; Ferres *et al.* 2021).

Climate and resource quality seem to be the most influential factors affecting giraffe's home ranges, and can explain a majority of the differences within and between regions (Deacon and Smit, 2017). Rainfall in particular has been shown to explain large amounts of variation in home range sizes across different populations of giraffe; giraffe in areas with higher annual rainfall tend to have smaller ranges (Deacon and Smit, 2017; Knüsel *et al.*, 2019). This reflects previous research where home range size estimates have generally been larger in more arid regions (see Fennessy, 2009), compared to those with higher levels of rainfall (see Berry, 1978; Knüsel *et al.*, 2019; van der Jeugd and Prins, 2000). Better resource quality, as a consequence of more rainfall, means that giraffe have to travel shorter distances to meet their resource requirements (Fennessy, 2009; Knüsel *et al.*, 2019). This may also explain seasonal variations observed in home range size. Pendu and Ciofolo (1999) studied a population of 63 giraffe in Niger and noted that the mean home range size during the dry season was twice that of the rainy season (90.7 km² and 46.6 km², respectively). Mcqualter *et al.*, (2015) and Caister *et al.* (2003) also found that home range sizes were larger in the dry season, and Deacon and Smit (2017) found that in the wet season, giraffe ranged an average of 177 km², whilst in the dry season this increased to 245 km². This is likely due to the need to travel further in search of food and water resources (Pendu and Ciofolo, 1999). Similarly, in drought conditions, giraffe spread out in search of food (Dagg, 2014b). Pellew (1984a) agrees that the small-scale changes in home range that they observed were due to the changed distribution of food resources. This may also explain the findings by Okello *et al.* (2015) that population densities of Masai giraffe are higher in the wet season, although Pellew (1984a), also looking at Masai giraffe, found that

seasonality did not appear to affect population densities. Caister *et al.* (2003) found that giraffe core ranges changed between seasons, utilising different habitats for the dry and wet season. Contrary to this, Mcqualter *et al.* (2015) showed that home range differences for giraffe in northern Botswana during the wet and the dry season overlapped and were not mutually exclusive.

Although giraffe are generally considered water-dependent species, because they can get water from their browse, it makes the extent to which they drink – and consequently the extent to which surface water availability directly influences their home range – unclear (Dagg and Foster, 1976; Redfern *et al.*, 2003; Shorrocks, 2016; Smit *et al.*, 2007; Western, 1975). One instance where giraffe have shown no reliance on surface water is in the northern Namib desert (Fennessy, 2009). In other populations, giraffe have been shown to stay at least 10 km away from water points (de Leeuw *et al.*, 2001), perhaps to reduce predation (Davidson *et al.*, 2013), yet also move to habitats where water is more available (Okello *et al.*, 2015). Surface water may indirectly influence a giraffe's habitat choice as they show a preference for succulent browse (Mitchell, 2021b; Owen-Smith, 1988; Sauer *et al.*, 1982).

Habitat type can also be a key factor in determining giraffe's home ranges. Deacon and Smit (2017) found that giraffe prefer more open habitats, favouring less-dense woodland, yet would avoid areas such as grassland and forbland. In a study on Masai giraffe, Knüsel *et al.* (2019) found that vegetation type did not affect giraffe home ranges, but the size of giraffe home ranges did increase near areas of increasing human population density. This is likely due to the associated degradation of habitat. Males and females have different habitat preferences: females are more likely to occupy open habitats, whereas males prefer dense woodland areas or thickets (Bercovitch and Berry, 2010; Foster, 1966; Foster and Dagg, 1972). This is possibly due to differences in height, with some males being tall enough to reach food which is inaccessible to females (Foster and Dagg, 1972; Mramba *et al.*, 2017; Pellew, 1984a), or due to the presence of calves, where open habitats enable higher levels of vigilance against predators (Foster and Dagg, 1972; Ginnett and Demment, 1999). Similarly, females nursing calves may avoid certain areas and food sources due to the high tannin levels in some forage species which makes giraffe milk less palatable to their young (Caister *et al.*, 2003).

Across Africa, giraffe have experienced habitat loss through direct human modification of

ecosystems as well as climate-driven shifts in vegetation structure. The conversion of savanna and woodland to cropland, human settlements, and infrastructure has caused widespread loss and fragmentation of giraffe habitat, particularly for Masai, Nubian and Reticulated giraffe (Marneweck *et al.*, 2025). West African giraffe have historically faced extensive conversion of their key habitat to agriculture, with most of the remaining population now restricted to communal lands in Niger (Marneweck *et al.*, 2025). At the same time, ecosystem-level change is also occurring in the absence of direct land-use transformation: changing rainfall patterns combined with increasing atmospheric CO₂ are linked to changes in fire regimes and shifts in the tree–grass balance, including woody encroachment and drought-driven tree mortality (Trisos *et al.*, 2022).

Drought has been identified as a threat for giraffe in Eastern and Central Africa and for West African giraffe in Niger (Muller *et al.*, 2018), and increases in drought and associated tree mortality have been observed in arid parts of the Horn of Africa and southern Africa, potentially occurring within the ranges of Reticulated and Southern giraffe (Trisos *et al.*, 2022). Drought can reduce giraffe habitat quality by causing tree mortality, increasing wildfire risk, and reducing the availability and nutritional quality of browse (Case *et al.*, 2019). In contrast, IPCC AR6 reports that woody plant expansion has been observed across large areas of the western and central Sahel and parts of southern, central and west Africa (Trisos *et al.*, 2022) – regions that may overlap with the ranges of Northern and some Southern giraffe. Together, these processes show that giraffe habitat is changing not only in extent, but also in ecosystem structure and function, and that the balance of anthropogenic and climatic drivers varies among species and regions.

The strong influence of climate and resource availability on giraffe home range size and habitat use has implications for how giraffe may respond to future climate change. Larger home ranges in more arid environments and during dry seasons indicate that giraffe already range more widely when food and water resources are limited. Under climate change, increases in temperature and changes in rainfall patterns may further alter the availability and distribution of forage and surface water, potentially requiring giraffe to travel greater distances to meet their resource requirements. However, the extent to which giraffe can respond to such changes by adjusting their home ranges is likely to be influenced by habitat fragmentation, land-use change, and other barriers to movement.

2.3.5 Diet

Giraffe are browsers; they predominantly eat leaves and shoots, but will also eat fruits, pods/seeds, and flowers from trees and shrubs (Caister *et al.*, 2003; Hall-Martin, 1974; Mitchell, 2021c; Pellew, 1984a). They rarely eat herbs, climbers or vines (Leuthold and Leuthold, 1972; Pellew, 1984a). Each day, male and female giraffe consume a respective average of 1.6% and 2.1% of their bodyweight (Pellew, 1984b), and spend between 43% to 53% of their time feeding, although this changes between seasons (Pellew, 1984a). Given the skew in the literature towards Masai and Southern giraffe, it is hard to determine whether there are differences in the diets of giraffe species, and whether these differences would be due to an absence of the plant or a preference for different species. The giraffe's typical diet also changes between the dry season and the wet season. Generally, giraffe prefer deciduous species; they consume more deciduous species during the wet season but when these are less available during the dry season, they consume more evergreen species (Parker and Bernard, 2005).

Giraffe have been noted to have a large and varied diet in terms of the species they eat. Leuthold and Leuthold (1972) observed giraffe in the Tsavo National Park, and found that they consumed a total of 66 plant species. Innis (1958) found that, in the dry season, the giraffe at Fleur de Lys consumed 32 species of plants. Despite this, a large portion of giraffe's diets seem to constitute *Vachellia* spp. and *Senegalia* spp. (both formally known as *Acacia* spp.) (Brenneman *et al.*, 2009; Dagg and Foster, 1976; Mahenya *et al.*, 2016). In particular, *Senegalia nigrescens*, previously known as *Acacia nigrescens*, seems to be a preferred food source for giraffe where it occurs (Fleming *et al.*, 2006; Furstenburg and van Hoven, 1994; Hall-Martin, 1974). Species of the *Combretum*, *Boscia* and *Grewia* genera are also important food for giraffe (Fennessy *et al.*, 2003; Leuthold and Leuthold, 1972; Muller *et al.*, 2018a; Sauer, 1983; Sauer *et al.*, 1977). There are, however, some discrepancies between giraffe diets, with some populations consuming species that others do not (Dagg and Foster, 1976).

In South Africa, giraffe have been shown to favour previously-termed 'Acacia' species. In a study by Parker and Bernard (2005), *Vachellia karroo* was shown to make up the highest proportion of giraffe's diet across three separate sites. This was followed by several *Searsia* spp. (previously *Rhus* spp.), specifically *S. longispina* and *S. pallens*, but this varied by site. The giraffe consumed a total of 48 plant species, but this ranged from 22 to 37 species at each

site, possibly influenced by site size and species' presence (Parker and Bernard, 2005). At another site in South Africa, where giraffe have been introduced, around 80% of the giraffe's diet was thought to be *Vachellia haematoxylon*, and they also browsed on *Vachellia erioloba* (Viljoen *et al.*, 2017).

In Niger, West African giraffe follow a slightly different diet. Ciofolo (1995) documented that Mimosaceae and Capparidaceae species (noted by Ciofolo to include several *Acacia*, *Dichrostachys*, and *Boscia* species) constituted the majority of the giraffe's diet. A more recent study by Caister *et al.* (2003) found that *Vachellia nilotica*, *Vachellia seyal*, and *Combretum glutinosum*, were the plants most favoured by West African giraffe in the dry season, although this preference varied by site, age and sex. Sex differences in feeding preference have also been noted in giraffe populations in Kenya (Young and Isbell, 1991).

In the Seronera region of Tanzania, the preferred food of Masai giraffe is *Vachellia drepanolobium* (Strauss and Packer, 2015). They also browse on the new shoots on *Vachellia tortilis*, yet rarely feed on *Vachellia robusta* (Strauss and Packer, 2015). This is a slight change in food preference from that reported in an earlier study by Pellew (1984a), whereby the favoured species were *V. tortilis*, *Vachellia xanthophloea*, *Vachellia hockii*, *Senegalia senegal*, *Grewia bicolor*, and *Grewia arborea* (previously *G. fallax*). This change in dietary preference seems to be due to a reduction in the abundance of these species (Strauss *et al.*, 2015; Strauss and Packer, 2015). *V. drepanolobium* and *V. xanthophloea* are also a preferred food for giraffe populations in Kenya, along with *Vachellia seyal* and *Balanites glabra* (Young and Isbell, 1991).

The reliance of giraffe on a relatively narrow set of woody browse species, despite the consumption of a wide range of plant species, has implications for their vulnerability to climate change. Although giraffe consume many plant species, diets across regions are often dominated by a small number of key genera, particularly *Vachellia* and *Senegalia*. Changes in rainfall patterns, increased drought frequency, or rising temperatures may affect the distribution, productivity, and nutritional quality of these preferred browse species, potentially reducing food availability even where giraffe remain present. Seasonal shifts in diet, and documented changes in preferred food species over time, suggest that giraffe can exhibit some dietary flexibility, however, such flexibility appears to be constrained by local plant availability. Climate-driven changes to vegetation composition

may therefore disproportionately affect giraffe populations that are already restricted to fragmented habitats or limited plant communities, potentially influencing survival, reproduction, and population persistence under future climate change.

2.3.6 Predators

Giraffe predators have been recorded to include lions, hyenas, cheetahs, and leopards (Berry, 1973; Foster and Dagg, 1972; Mutoro *et al.*, 2022; Pienaar, 1969; Pratt and Anderson, 1979). Lions are the main predator of giraffe, attacking both young and adult giraffe (Berry, 1973; Brenneman *et al.*, 2009; Dagg, 2014a; Hall-Martin, 1974), but calves are more vulnerable to lion predation than adults (Strauss and Packer, 2013).

Giraffe are considered a secondary prey species for lions (Lee *et al.* 2016b; Owen-Smith and Mills, 2008). A study by Loveridge *et al.* (2006) found that giraffe were the fourth most preyed upon species (following buffalo, elephants, and wildebeest) and accounted for 9% of lion kills in Hwange National Park (HNP), Tanzania. Davidson *et al.* (2013) had similar findings in a later study looking at lions in HNP, finding that giraffe accounted for 12% of their prey. In terms of biomass, giraffe made up 7% of a male lions' diet, and 18% of a female lions' diet (Davidson *et al.*, 2013). Additionally, in the HNP, giraffe account for 7% of a Hyena's diet (Drouet-Hoguet, 2007, as cited by Valeix *et al.*, 2009), although it is unclear whether this is from scavenging or direct predation.

In some instances, lions have been shown to prey on giraffe more often than expected based on their abundance in the area (Hayward and Kerley, 2005; Muneza *et al.*, 2021), but Davidson *et al.* (2013) found that lions will preferentially avoid megaherbivores such as giraffe when there are other prey species present. As such, although predation pressure from lions is negatively correlated with calf survival, the presence of migratory ungulates (a lion's primary prey) reduces predation on giraffe calves (Lee *et al.*, 2016a; Lee *et al.* 2016b). Strauss *et al.* (2015) found that there was no relationship between the number of giraffe killed each year and the population size of lions in the study area. Over a period of ~45 years (mid 1970s to 2015) in the Serengeti National Park, the ratio of lions to giraffe increased sevenfold, yet there was an increase in calf survival, possibly due to the increase in abundance of wildebeest and zebra (Strauss *et al.*, 2015). Research by Strauss and Packer (2013) supports this; they found that lions killed more calves during the dry season when

there are fewer migratory ungulates. However, this may also be due to the change in browse availability forcing giraffe into areas which make them more susceptible to lion attacks (Pellew, 1984a; Strauss and Packer, 2013).

The presence and abundance of predators can have various effects on the behaviour of prey species. In the case of giraffe, it has been shown that the presence of predators can affect their habitat selection, vigilance behaviour, and sleep patterns (Burger *et al.*, 2020; Cameron and du Toit, 2005; Périquet *et al.*, 2010; Thaker *et al.*, 2011). Valeix *et al.* (2009) found that giraffe increased their preference for grassland when lions were nearby and decreased their use of bushland. This may be due to grassland providing a greater detection rate of predators and hence aiding in anti-predator behaviour (Courbin *et al.* 2019; Valeix *et al.*, 2009; Young and Isbell, 1991). Similarly, Thaker *et al.* (2011) found that giraffe would avoid areas that lions and leopards frequently used, although avoidance response did not correlate with threat level. They found that models which best predicted the presence of giraffe in Karongwe Game Reserve included avoidance of risky habitats, avoidance of sit-and-pursue predators (lion and leopards), and selection of predator-free habitat such as open woodland and scrub.

Davidson *et al.* (2013) found that lions tended to kill prey between 1 km and 4 km from waterholes, but the species that were generally killed closest to waterholes were giraffe and elephants. Whilst giraffe are drinking, their body position makes them particularly vulnerable to predators (Périquet *et al.*, 2010), and giraffe vigilance generally increases when drinking in areas with lions nearby (Périquet *et al.*, 2010). When visiting a waterhole, giraffe spend an average of ~40% of their time being vigilant, although they drink more frequently when in a larger group (Périquet *et al.* 2010). Vigilance is an important anti-predator behaviour. Larger groups of giraffe have a smaller proportion of individuals being vigilant (Marealle *et al.*, 2020). When giraffe are sleeping, and thus vulnerable to predation, they rely on a standing giraffe to remain vigilant against predators (Burger *et al.*, 2020). Given that calves are more susceptible to predation, it would be expected that the presence of calves would increase giraffe vigilance behaviour, but Cameron and du Toit (2005) found that this had no effect on the amount of time adults spend being vigilant.

Understanding predation patterns is important in understanding how climate change may indirectly impact giraffe species. Changes in rainfall, vegetation structure, and water

availability can alter both giraffe movement patterns and predator distributions, potentially increasing spatial overlap between giraffe and their primary predators. Dry-season conditions and drought may further elevate predation risk by concentrating giraffe near limited water sources or forcing movement through riskier habitats. As predator distributions are themselves climate-sensitive, understanding predator ecology provides important context for interpreting climate suitability and conservation priority areas for giraffe. This is particularly relevant for the modelling framework adopted in this thesis, which explicitly incorporates predator species distributions to assess how biotic pressures may interact with climate change to influence giraffe vulnerability.

2.3.7 Effects of seasonality

Giraffe are found in areas that have distinctively different climates throughout the year, primarily a wet season and a dry season. The above sections have shown how seasonality can affect food preference, herd size, and home range, but seasonality may affect giraffe in other ways.

Several studies have shown that seasonality can indirectly affect giraffe survival (Davidson *et al.*, 2013; Lee *et al.*, 2017; Strauss and Packer, 2013). Lee *et al.* (2017) showed that Masai giraffe calves have a higher chance of survival in the dry season compared to those born in the wet season. They postulate that this survival advantage is due to either a greater amount of maternal energy reserves, a higher protein concentration in browse which allows for supplemented energy reserves, or reduced predation of calves due to a lack of stalking cover. However, Davidson *et al.* (2013) found that giraffe and other browser species were more likely to be preyed upon by lions in the early dry season, whilst Strauss and Packer (2013) also found that, when looking at presumed lion kills in the Serengeti, significantly more giraffe died during the dry season. Recent research by Hart *et al.* (2021) contradicts the findings by Lee *et al.* (2017), as it was found that for Angolan giraffe, calves born in the wet season were more likely to survive past their first year.

Giraffe have been observed to alter their behaviour between the seasons. In the wet season, giraffe are more active after sunset, and spend correspondingly less time lying down and in a sleeping position (Burger *et al.*, 2020). Burger *et al.* (2020) postulate that this may be due to an increased sense of security during the dry season when the vegetation is less dense,

and giraffe have an increased view of predators.

Seasonality is therefore an important factor influencing giraffe behaviour, survival, and exposure to risk, and provides useful context for interpreting potential impacts of climate change. Many of the processes affecting giraffe fitness, including forage availability, movement behaviour, and predation risk, vary between wet and dry seasons. Projected changes in temperature and rainfall are likely to alter the timing, intensity, or duration of these seasonal conditions, which may disrupt patterns that giraffe currently use to respond to environmental variability.

2.3.8 Threats

The IUCN assessment published in 2018 identified several main threats to giraffe: habitat loss, civil unrest, poaching, and ecological changes (including climate change) (Muller *et al.*, 2018a). Habitat loss and poaching (both accidental and deliberate) are likely to be the most substantial factors causing population declines across all species/subspecies (Shorrocks, 2016), but each population of giraffe is exposed to different threats of varying severity (Dunn *et al.*, 2021; Muller *et al.*, 2018a).

Habitat loss, degradation, and fragmentation affecting giraffe can be caused by conversion of suitable habitat to agricultural land, deforestation, desertification from lack of rainfall, and human population growth (Ciofolo, 1995; Muller *et al.*, 2018a; Ogutu *et al.* 2014; Suraud *et al.*, 2012). Habitat loss and degradation affect most giraffe populations and is particularly important to consider for those populations which are already fractured and surviving in small, isolated areas. The IUCN report states that, for giraffe in West Africa, human-wildlife conflict and habitat loss from human population growth are the main threats (Muller *et al.*, 2018a). A threat assessment carried out on the most endangered subspecies, West African giraffe, compared the potential impacts of habitat loss, human population growth, poaching, population viability (due to the small number of individuals), and climate change, and found that their main current threat is habitat loss (Gašparová *et al.*, 2020). Their key habitat, called ‘tiger bush’, covers approximately 22,000 km² but is undergoing extensive overgrazing and deforestation (Morou *et al.*, 2011). This finding echoes earlier research by Ciofolo (1995) who found that West African giraffe habitat had been substantially decreased by desertification from reduced rainfall alongside

population growth and political decisions which encouraged overgrazing, soil cultivation, and destruction of vegetation. Similarly, in the Masai Mara and Tsavo National Park, Masai giraffe population declines in these areas have been attributed to a loss of woodland habitat (Leuthold and Leuthold, 1978; Ottichilo *et al.*, 2000).

Hunting giraffe is legal in Namibia, South Africa, Zambia, and Zimbabwe, but illegal hunting (poaching) occurs across all giraffe species' ranges and is another prominent threat that giraffe face (Dunn *et al.*, 2021). In the Serengeti alone, reports on illegal hunting suggest that between 3 and 200 giraffe can be killed each year (Strauss *et al.*, 2015). Driven by local and international markets, giraffe parts are often used for consumption, ornamental and medicinal purposes (Dunn *et al.*, 2021; Shorrocks, 2016). Poaching often occurs at the borders of Protected Areas (PAs), or in areas near human populations (Hofer *et al.*, 1996; Marealle *et al.*, 2010; Wato *et al.*, 2006). For example, in the Serengeti National Park, poaching on the border has been attributed as the prime cause of declining numbers of giraffe (Ogutu *et al.*, 2011). Poaching has been at least partly responsible for declines of populations of West African giraffe, Nubian giraffe, Kordofan giraffe, Masai giraffe, and Reticulated giraffe (Ciofolo, 1995; D'haen *et al.*, 2019; Lee *et al.* 2016a; Marealle *et al.*, 2010; Muller, 2018; Ogutu *et al.*, 2009, 2014; Ruppert *et al.*, 2021a; Sinclair, 1995; Strauss *et al.*, 2015; Suraud *et al.*, 2012; Waltert *et al.*, 2009). Poachers commonly use snares which are set in trees and catch giraffe around their necks (Hofer *et al.*, 1996; Muchaal and Ngandjui, 1999; Strauss *et al.*, 2015). However, snares set at ground level can also catch giraffe, regardless of whether they are the intended target (Strauss *et al.*, 2015). Adult giraffe are the most common age group caught in snares, and males are more likely to be caught than females (Strauss *et al.*, 2015). This sex bias can result in skewed sex ratios in populations of giraffe (D'haen *et al.*, 2019; Marealle *et al.*, 2010; Suraud *et al.*, 2012).

Civil unrest can threaten giraffe, but predominantly due to the associated increase in poaching. In the Ethiopian-Eritrean civil war, access to guns and increased demand for food meant that poaching of giraffe and other animals increased (Jacobs and Schloeder, 2001). Similarly, previous reductions in giraffe populations in Uganda have been partly attributed to civil unrest in neighbouring countries, which caused an increase in poaching (Brown *et al.*, 2019). Since the reduction in poaching here, giraffe populations have increased (Uganda Wildlife Authority, Accessed 11th June 2022). Before the Mozambique

civil war (1977-1992), giraffe populations had faced large range declines within the country (Giraffe Conservation Foundation, 2023a). The civil war caused an increase in poaching, and weak law enforcement during this time, and for several years after, caused population declines to the point that giraffe were thought to be extinct in the country (Giraffe Conservation Foundation, 2023a; Roque *et al.*, 2022). Outside of these instances, human-giraffe conflict is not often a threat for giraffe, and people that live near giraffe tend to have a positive view of the species (Ruppert *et al.*, 2021b). Giraffe are unlikely to damage crops because they browse on taller vegetation, but they have been noted to occasionally eat fruit such as mangoes from village trees (Ciofolo, 1995; Leroy *et al.*, 2009). They may also damage unfenced fields and gardens when they pass through them (Zabeirou, 2017).

In some areas, disease is considered a high-level threat to giraffe (KWS, 2009). Historically, rinderpest (now eradicated, see Njeumi *et al.*, 2012), gastroenteritis and anthrax have reduced giraffe populations, and in some instances been the limiting factor of giraffe population growth (Berry, 1973; Dagg and Foster, 1976). Anthrax can kill giraffe, but once detected, at risk individuals can be vaccinated to contain the outbreak (Kaitho *et al.*, 2013; Muturi *et al.*, 2018). Giraffe can be susceptible to parasite infestations, but it is unclear to what extent this can affect their health and mortality. Strauss *et al.* (2015) found that female giraffe had higher endoparasite loads than males, yet there was no apparent link between parasite load and giraffe age. It is also possible that giraffe receive some level of endoparasite resistance from the tannins in their food (Brenneman *et al.*, 2009). One disease which is potentially caused by parasites is Giraffe Skin Disease (GSD) (Mpanduji *et al.*, 2011); some studies have shown that fungi may be involved, but it is unclear if this is secondary to having the disease (Kiula *et al.*, 2021; Mpanduji *et al.*, 2011). GSD is relatively unstudied, but as of 2016 it had been seen in four species/subspecies of giraffe in the wild: Masai, Nubian, South African, and Angolan (Muneza *et al.*, 2016). It causes skin lesions that occur predominantly on forelimbs but can be seen anywhere on the body (Epaphras *et al.*, 2012; Lee and Bond, 2016; Muneza *et al.*, 2021, 2019, 2016). GSD seems to primarily affect adults, and in some populations, around 85% of individuals have GSD (Epaphras *et al.*, 2012; Mpanduji *et al.*, 2011; Muneza *et al.*, 2021, 2016). Although it does not appear to directly influence giraffe mortality, it has been suggested that when giraffe are afflicted with the disease they are more vulnerable to predators (Brenneman *et al.*, 2009; Muneza *et al.*, 2016). A study by Muneza *et al.* (2021) examined this and found that the severity of GSD

had a small positive correlation with the number of claw marks on an individual; they did not find any direct links between survival and severity of GSD. GSD is more prevalent in the wet season (Mpanduji *et al.*, 2011), but it is not known how seasonality may affect GSD epidemiology (Muneza *et al.* 2017).

Extreme weather and climate changes are an increasingly prominent threat for giraffe (Muller *et al.*, 2018a). Few pieces of research have thus far directly linked climate change to current population declines in giraffe, although some have postulated that it has compounded the effects of other events, leading to range reductions (O'Connor *et al.* 2019). A study published in 2009 found that a sudden decrease of Nubian giraffe in Kenya closely followed an El Niño event (Brenneman *et al.* 2009). The study suggested that the climatic variability combined with a population already near its carrying capacity resulted in less available browse, restricting giraffe to one area of the park with their remaining food source, *V. xanthophloea*. Extreme climate and weather events, such as drought, can lead to increased giraffe mortality (Mitchell *et al.*, 2010; Okello *et al.*, 2015). Drought primarily impacts giraffe by reducing the availability and quality of browse, which can weaken individuals and lead to starvation (Mitchell *et al.*, 2010). In 2008, 26 giraffe died because of drought in Zimbabwe (Mitchell *et al.* 2010), and droughts in the 1970s and 1980s largely worsened the decline of West African giraffe, which were already under pressure from extensive poaching (Caister *et al.*, 2003; Ciofalo, 1995). In some cases, giraffe are able to withstand periods of drought and have been noted to suffer under unusually cold and wet periods (Walker *et al.*, 1987).

Given the multitude of threats facing giraffe, climate change is likely to act as an additional pressure that compounds existing stressors. Habitat loss, fragmentation, and reduced population size may limit the capacity of giraffe populations to respond to changing climatic conditions, increasing their vulnerability to climate change.

2.3.9 Conservation

To develop effective conservation plans for giraffe, it is important to have an agreement on the taxonomic classification of the different populations, as well as an identification of which habitats are most suitable for giraffe (Bercovitch and Deacon, 2015).

Having a consensus and agreed taxonomy for a species is important for several reasons. If too many species are recognised, it may dilute the resources available to each species and affect decisions relating to captive breeding and genetic rescue (Frankham *et al.*, 2012; Zachos *et al.*, 2013). Conversely, if individual species are not appropriately recognised, failure to identify threatened species and implement appropriate conservation actions becomes more likely (Gippoliti *et al.* 2018). In the case of giraffe, the recognition of four species has large implications for their conservation. Currently, giraffe are listed as one species that is categorised as vulnerable under the IUCN (Muller *et al.*, 2018a), yet if they were considered as four separate species, some of the species may be upgraded to a higher threat level (Winter *et al.* 2018).

Translocations and PAs have been key to the conservation of giraffe thus far. Translocations have been used to reintroduce giraffe to areas where they were extirpated, to establish new populations in areas such as game reserves, and to supplement existing populations (Shorrocks, 2016; Winter *et al.*, 2019). Most giraffe translocations have involved moving giraffe into PAs or fenced areas in places where they had been extirpated (O'Connor *et al.*, 2019). A majority of giraffe populations are currently found in PAs (Strauss *et al.*, 2015) and it is estimated that ~29% of total giraffe range is in Government-managed PAs (O'Connor *et al.*, 2019). Many giraffe, particularly Angolan and Reticulated giraffe, are found in community conservancies (Kiffner *et al.*, 2024; O'Connor *et al.*, 2019). In Kenya, all populations of Nubian giraffe are found in either PAs or private reserves, and have been translocated there following extirpation of the natural populations (Brown *et al.*, 2019). Despite this, in some places, such as Kenya, giraffe are found to be more abundant outside the PAs in areas such as ranches (Ogutu *et al.* 2011). As such, conservation actions should encompass both protected and unprotected areas in order to increase connectivity between populations and safeguard giraffe habitat (Okello *et al.*, 2015).

To re-establish populations lost to poaching and civil unrest, the Giraffe Conservation Foundation (GCF) and their partners have started translocating giraffe into Mozambique (GCF, 2023b), and are planning to move a total of 350 giraffe to bolster the initial population of 250 (GCF, 2021). Some key considerations for translocating giraffe are: habitat suitability, particularly in terms of the suitability and abundance of food and water; the taxonomy of the individuals being moved and the individuals at the destination; the

social associations of individuals; the predation risk; and whether there may be negative effects from competition with other herbivores (Bond *et al.*, 2021a; Hall-Martin and Graaff, 1978; Muller *et al.*, 2020; Shorrocks, 2016). Population viability analyses can be carried out to assess the feasibility of translocating giraffe (Lee *et al.*, 2020; Muller *et al.* 2020). The importance of considering genetics when translocating species is highlighted in a recent paper by Winter *et al.* (2019). The giraffe population in the Republic of Malawi has a diverse translocation history, but by examining the genetics of the resident populations of giraffe, Winter *et al.* (2019) concluded that any further translocations here should likely be South African giraffe. This would help conserve genetic diversity and avoid inbreeding depression. Coimbra *et al.* (2022) also highlight the need to understand population genetics when looking to use populations as a source for translocations to new areas.

As described previously, poaching is a major threat to many giraffe populations. Giraffe, as a single species, were added to CITES Appendix II in 2019, which aims to increase monitoring of the international trade of the species (CITES, 2019). The true extent to which international trade drives giraffe poaching is still unclear, and Dunn *et al.* (2021) suggest that local-level monitoring and research may be more useful for informing giraffe conservation. Another common technique to combat poaching is anti-poaching patrols. These can be successful in reducing poaching, but in some areas, populations continue to decline even after anti-poaching patrols have been implemented (Suraud *et al.*, 2012). Increased government enforcement of anti-poaching legislation combined with initiatives which promote education of local people can be effective in reducing poaching (Ruppert *et al.*, 2021a; Suraud *et al.* 2012). A study by Ruppert *et al.* (2021a) found that there had been a decline in giraffe meat consumption in Kenya after the introduction of a conservation program. The program involved monitoring the group of Reticulated giraffe, tracking giraffe mortality as well as community engagement. In the case of West African giraffe, due to the lack of predators, poaching had been the main factor limiting the population size (Suraud *et al.*, 2012). The successful conservation and high population increase from 50 individuals in 1996 to ~220 in 2009 was attributed to stronger government enforcement of anti-poaching legislation and community education (Suraud *et al.*, 2012).

Collectively, these conservation approaches highlight the importance of identifying areas where giraffe are most likely to persist under a changing climate. Given that climate

change is expected to alter the distribution and suitability of giraffe habitat, conservation strategies that rely on protected areas and translocations will increasingly depend on an understanding of where suitable climate and habitat are likely to be retained. This is particularly important for fragmented and range-restricted giraffe species, where their ability to track suitable climate may be limited. Identifying climatically stable areas, therefore provides critical context for prioritising conservation actions and supporting long-term giraffe persistence under future global warming.

2.4 Previous research and knowledge gaps

Research examining climate and habitat suitability for species is becoming increasingly common because of its utility in identifying sites for species translocations or even aiding in the location of undiscovered populations (Draper *et al.*, 2019; McCune, 2016; Rhoden *et al.*, 2017). Recently, research has been published which maps the fine-scale habitat suitability for Reticulated giraffe and a small portion of Masai giraffe range (Crego *et al.*, 2023; Muthiuru *et al.*, 2024).

Crego *et al.* (2023) modelled the habitat suitability of Reticulated giraffe for 2019-2020 across the entire species' range using random forest algorithms. Predictor variables included the Normalised Difference Vegetation Index (NDVI), Bare Soil Index, surface ruggedness, and woody vegetation proxies. Outputs showed that the western portion of the range had the most areas of suitable habitat (Figure 2.2).

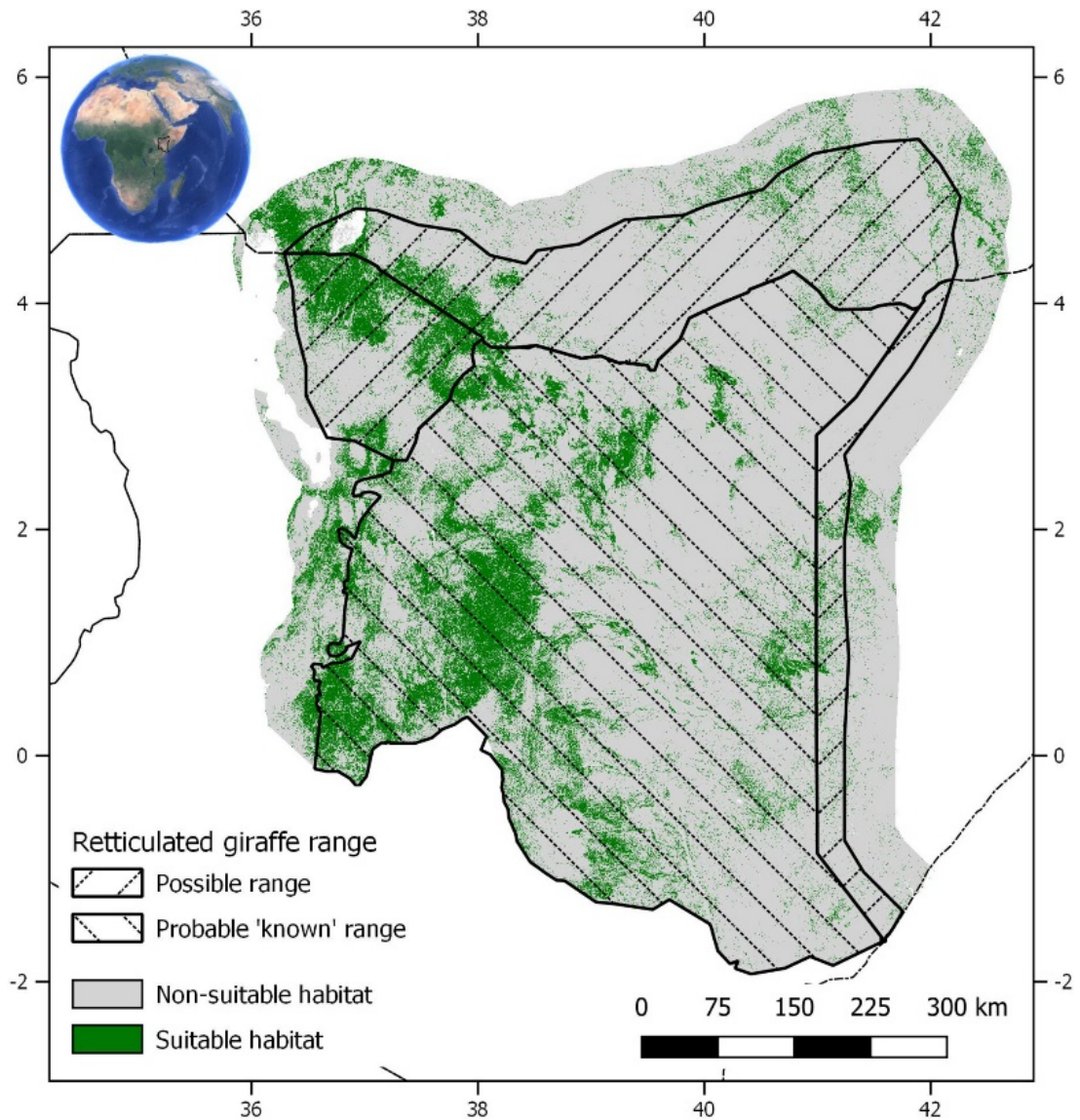


Figure 2.2: Binary habitat suitability map for Reticulated giraffe at 30 m spatial resolution for the period 2019-2020. Green areas represent suitable habitat and grey areas are non-suitable habitat. The Reticulated giraffe's range is shown as a hatched area with black border, with the direction of the hatched lines differentiating between the probable 'known' range and the possible range. This figure is from Crego *et al.* (2023).

To map Masai giraffe habitat suitability for the Tsavo-Mkomazi landscape in Kenya and Tanzania, Muthiuru *et al.* (2024) used random forests and model variables of elevation, global human modification, mean annual precipitation, surface roughness, vegetation condition, and woody vegetation. They produced a habitat suitability map (Figure 2.3) and used this to model landscape connectivity within the region. The main predictors of habitat suitability were found to be human modification, rainfall, and elevation, and 17% of potential suitable habitat in the landscape was found to be outside of protected areas.

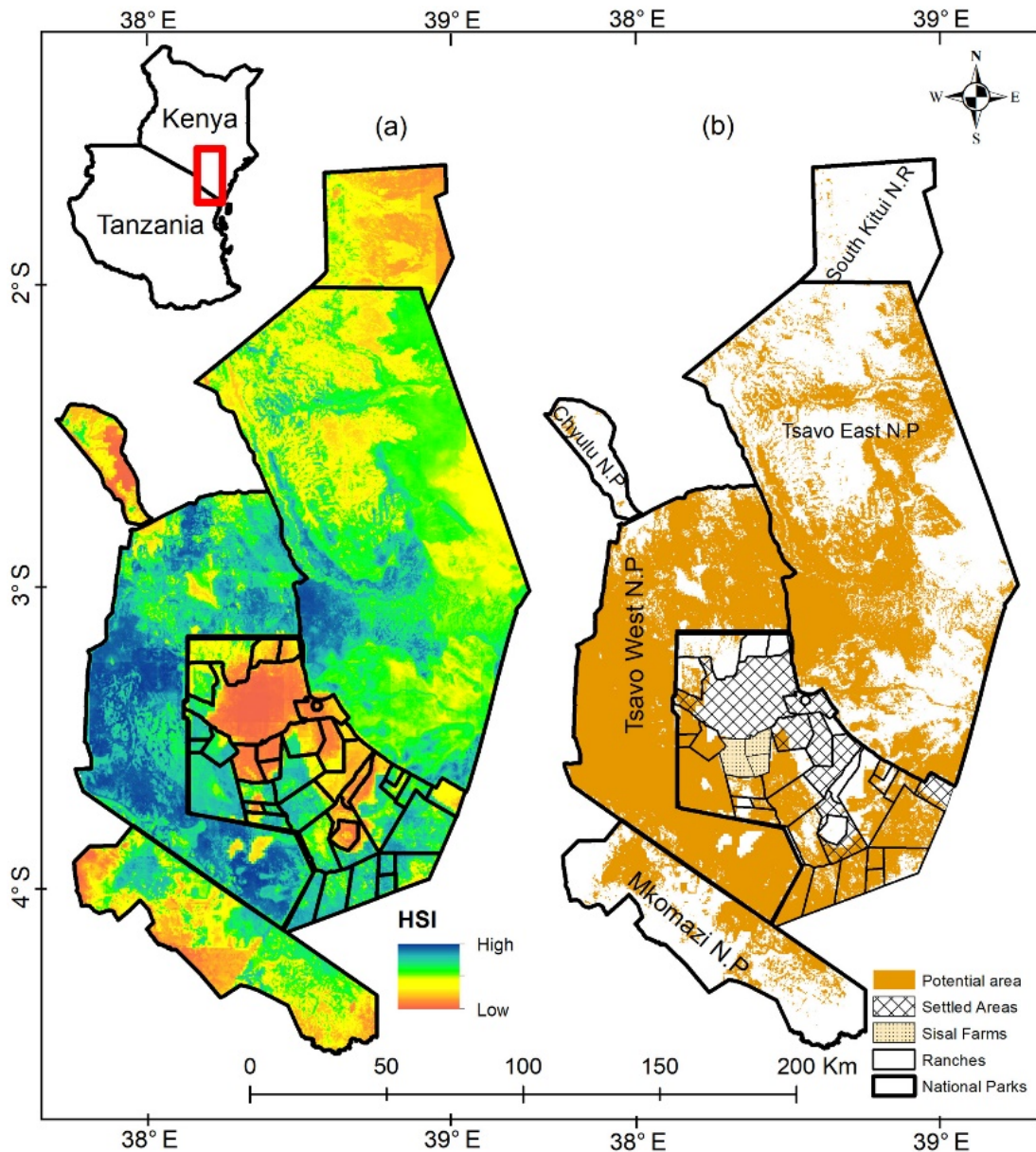


Figure 2.3: (a) Habitat suitability Index (HSI) from high (blue) to low (orange) and (b) potential suitable habitat for Masai giraffe (orange) in the Tsavo-Mkomazi landscape. Figure from Muthiuru *et al.* (2024).

These habitat suitability maps are hugely useful for conservation practitioners in guiding management decisions and spatially explicit conservation actions. However, the focus on near present-day habitat suitability and lack of consideration of climate change limits their long-term utility and leaves a large knowledge gap. Combining these outputs with projections of climate change impacts would allow for well-informed, long-term conservation strategies which are optimised for climate change adaptation and resilience.

Research investigating the potential impact of climate change on giraffe is limited to two

studies – Martínez-Freiría *et al.* (2016) and Bond *et al.* (2023). Both studies are summarised below alongside key research gaps which remain.

Martínez-Freiría *et al.* (2016) examined the effect of climate change on both giraffe and elephants (*Loxodonta africana*), specifically looking at how the inclusion of historical occurrence data can influence species distribution model (SDM) outcomes. In this study, information on historical and current distribution of giraffe was gathered from ~30 references, and giraffe were modelled as one species using Generalized Linear Models, Generalised Additive Models, Maxent, and Artificial Neural Networks. The climate suitability was projected to 2070 under RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, using seven general circulation models, chosen based on their regional performance for Africa. Martínez-Freiría *et al.* (2016) found that the use of historical data largely increased the projected amount of suitable climate under the different climate change scenarios.

This research has highlighted the impact of human-mediated species' range contraction on the performance of SDMs. However, since this study was published, updates on giraffe taxonomy have shown there are likely four species (Coimbra *et al.*, 2021). As a result, the grouping and subsequent modelling of giraffe as one species in the research by Martínez-Freiría *et al.* (2016) limits the applicability of their findings. Given the varying distributions of giraffe species across Sub-Saharan Africa, the different species likely inhabit distinct climate areas and may have different climatic niches, requiring separate climate suitability models. Furthermore, the research by Martínez-Freiría *et al.* (2016) projects climate suitability using four emission scenarios at only one time-frame (2070), and does not explore the impacts of non-climatic anthropogenic threats on giraffe in tandem with climatic factors, thus falling short of the holistic focus required to inform conservation actions.

More recently, Bond *et al.* (2023) developed an individual-based model (IBM) to examine the potential impacts of anthropogenic and climate changes on a population of Masai giraffe in the Tarangire Ecosystem, Tanzania. The results of this model showed that increased law enforcement, and the subsequent decrease of poaching, had the greatest impact on limiting declines in female giraffe abundance. The climate change considerations in this model were restricted to a link between increased rainfall anomalies and reduced giraffe survival. Simulations were run with an increased frequency of

above-average rainfall anomalies by either 10% or 20%. Other factors considered by Bond *et al.* (2023) include the season of calf birth, predation pressure, carrying capacity, dispersal probability, distance to human settlements, habitat fragmentation from human infrastructure, and changes to predation pressure from either reduced lion presence or reduced lion primary prey. This research provides valuable insights for conservation actions in this study area, but these fine-scale approaches are only possible for small- to medium-scale study areas where there is detailed and sufficient knowledge of the local landscape, study species' demographic data, law enforcement and legal frameworks, and local human elements. Additionally, some key aspects of the potential impact of climate change on giraffe are overlooked. For example, there are no considerations for the impact of temperature, or the impact of climate change on giraffe predators and food species, and only two scenarios (10% and 20% increase in the frequency of rainfall anomalies) are accounted for.

In both of these studies, only one element of climate change is examined – either changes to mean climate (Martínez-Freiría *et al.*, 2016) or simple increases in the frequency of an extreme climate event (Bond *et al.*, 2023). The ways in which climate change might impact species is multifaceted and complex, including changes to biotic interactions and the duration and intensity of extreme climatic events. By not accounting for the complexities of climate change impacts, previous research has likely underestimated the vulnerability of giraffe to climate change. Moreover, treating giraffe as a single species, or only focusing on one population does not adequately capture the varied species-specific exposure and responses to climate change.

This thesis addresses these limitations and knowledge gaps by integrating species-specific projections of climate suitability across multiple global warming levels with concurrent changes in climate-mediated biotic interactions and non-climatic anthropogenic threats. This allows for a better understanding of how climate change may affect each giraffe species and subspecies, and supports the development of climate-resilient conservation actions now and in the future.

Specifically, Chapter 3 'Assessing the climate change exposure of giraffe populations within their current geographic ranges' explores the research question: '*What is the projected exposure of each giraffe species and subspecies to climate change within their current*

geographic range?'. In this chapter, changes in temperature and precipitation variables are quantified, and the potential emergence of novel climates is investigated to highlight areas where species' climatic tolerances may be exceeded and where higher adaptation effort may be needed.

Chapter 4 'Identifying areas of climate change refugia as a least-regrets conservation strategy for giraffe species' adds to Chapter 3 by using correlative Species Distribution Models (SDMs) to answer the following research question: *'For each of the four giraffe species, how is suitable climate projected to change, and are there any areas of climate refugia?'*. This chapter uses multiple SDM algorithms to make projections more robust against individual model uncertainties, and uses projected climate data from 22 CMIP6 General Circulation Models (GCMs) to account for uncertainties between climate models. Mapping climate suitability separately for each of the four species of giraffe reflects potential species-specific climatic niches, and outputs are linked to specific global warming levels rather than time frames, allowing for flexible interpretation relative to real-world warming levels. Given the findings of Martínez-Freiría *et al.* (2016), SDMs incorporating historical occurrence records are included as a sensitivity analysis in the supplementary materials, while models based on contemporary distributions are presented in the main chapter due to uncertainties in assigning historical occurrences to the revised four-species taxonomy.

Chapter 5 'Beyond mean climate: A comprehensive approach to prioritising areas for giraffe conservation under climate change' addresses the research question: *'Where are the priority areas for the conservation of each giraffe species and subspecies when multiple projected climatic and anthropogenic pressures are considered simultaneously?'*. This chapter incorporates non-climatic factors such as land-use and projections of human population alongside climate suitability projections to develop a holistic view of priority areas for giraffe conservation as well as those areas which may need higher adaptation effort to remain suitable. Along with Chapter 3, this chapter integrates projections of extreme wet and extreme dry climate to assess the impact of changes to relevant extreme climatic events.

Chapter 6 'GiraffeClim: A Web-Based Tool for Exploring Climate Change Impacts on Giraffe' introduces a freely available web application which is designed to enhance the

accessibility and usability of the outputs from this thesis. Chapter 7 'Conservation Implications, Limitations, and Conclusions' consolidates the outputs from the previous chapters in the context of species- and subspecies-specific conservation actions.

The outputs of this thesis aim to be complementary to existing finer-scale habitat suitability assessments and provide conservationists with a comprehensive understanding of giraffe vulnerabilities, future conservation priorities, and areas which may need higher levels of adaptation effort to support viable giraffe populations in the future.

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Assessing the climate change exposure of giraffe populations within their current geographic ranges

Abstract

Whilst methods exist to project how species distributions may change under future global warming scenarios, there is significant uncertainty surrounding whether species will be able to disperse successfully to these areas. Understanding projected climate changes within species' current geographic ranges is therefore a crucial first step in climate change-informed conservation planning, providing conservation practitioners with an insight into the most vulnerable populations and most appropriate adaptation measures. Giraffe have large range areas and the ability to travel long distances, but their movement can be particularly impacted by fencing and fragmented landscapes. In this chapter, giraffe range maps were used to evaluate the exposure of all four suggested species of giraffe, and their subspecies, to climate change. Hierarchical cluster analyses and climate change projections under multiple global warming scenarios were used to assess the extent to which populations experience similar climates, and how these climates are projected to change. Results showed that the extent of exposure varies between species and subspecies. Angolan and South African giraffe (subspecies of Southern giraffe) are projected to experience the largest increase in temperature and the largest decrease in precipitation, respectively. At 2°C of global warming above pre-industrial levels, novel climate conditions

– those outside the bounds of the observed climate in the species' current geographical range – are projected in over half of each (sub)species' geographic ranges, except for Masai giraffe. At 3.2°C of global warming, most species are projected to face novel climatic conditions across the majority of their current range areas, posing potential challenges for in-situ conservation.

3.1 Introduction

The effect of climate change on species' ranges has been discussed widely for decades, with an abundance of literature either documenting observed range changes or projecting future range changes (see Chapter 2, section 2.1.1 'Geographic range changes'). Whilst tools such as species distribution models (SDMs) can be used to project species' potential distribution under climate change scenarios (Elith and Leathwick, 2009), there are many uncertainties surrounding the future realisation of these range changes. Several factors can influence whether a species disperses to the projected geographic range, such as a lack of dispersal ability, caused by factors such as small size (Jenkins *et al.*, 2007); dispersal barriers, such as fenced protected area boundaries or fragmented landscapes (Caplat *et al.*, 2016); or plasticity and autonomous adaptation allowing species to persist in-situ (Chevin *et al.*, 2010). These factors can affect species in different ways. For instance, while large mammals are generally capable of traveling long distances, their movement can be constrained by roads, agricultural areas, human infrastructure, and fences (Jones *et al.*, 2022). Dispersal barriers themselves can also be dynamic (Caplat *et al.*, 2016) – many man-made barriers can be built or removed at any point, and natural processes, such as flooding, can cause new dispersal barriers or increase connectivity (Zeigler and Fagan, 2014). Even if species are able to disperse to track areas of suitable climate, there are many factors which could influence whether they are able to colonise and persist in the new area (Pacifci *et al.*, 2020). With the dynamic nature of dispersal barriers, and the uncertainty surrounding how climate change may itself impact species dispersal (Travis *et al.*, 2013), understanding how species may be exposed to climate change within their current geographic range is increasingly important. Additionally, where it is known that species exist within protected areas, or in highly fragmented landscapes, this information can be used to identify populations that are most exposed to changes in climate and inform

conservation priorities and management plans.

Giraffe are capable of travelling large distances, covering hundreds of kilometres each month (Deacon *et al.*, 2023). They have been known to cross roads and agricultural areas if necessary (Ferres *et al.*, 2021), but their movement can be largely constrained by fences (Crego *et al.*, 2021). Around 30 percent of total giraffe geographic range exists within Government-Managed Protected Areas; between species this ranges from 4% (Reticulated giraffe) to 59% (Masai giraffe) (O'Connor *et al.*, 2019). When existing outside of a protected area, one of the main factors hampering their dispersal ability is fences (Crego *et al.*, 2021). This is particularly true in areas of fragmented landscape, where giraffe ranges coincide with human populations and fenced agricultural land. The erection of fences within key giraffe range areas is becoming an increasingly relevant issue. For example, in the Greater Mara area in Kenya, the amount of fenced area increased by 170% from 2010 to 2020, resulting in a total of 19% of the entire region being fenced land (Løvschal *et al.*, 2022).

This surge in dispersal barriers makes it increasingly important to understand the potential climate changes within current range areas and assess the vulnerability of each giraffe population. In cases where giraffe exist within bounded protected areas, an understanding of potential climate changes within these areas under multiple warming levels is important. It can help to equip managers and conservationists with the information to pre-empt potential adaptations that may be needed (such as watering holes) to support the species within the reserve. Additionally, targeted application of fence gaps to allow movement out of protected areas which are highly exposed to climate change could be beneficial, and giraffe have been known to make use of these fence gaps (Dupuis-Désormeaux *et al.*, 2016).

The aim of this chapter is to assess the exposure of each giraffe species and subspecies to projected climate change within their current geographic ranges. To achieve this, projected shifts in climatic similarity between populations were examined, changes in seasonal climate variables and drought conditions were quantified, and the exposure of populations to novel climatic conditions was evaluated. Climatic similarity between populations was explored using agglomerative hierarchical clustering, using observed and then projected temperature and precipitation variables averaged across each (sub)species' geographic range. Following this, observed and projected changes in average seasonal temperature

and precipitation variables were quantified for each (sub)species' geographic range, highlighting those most exposed to changes in climate at global warming levels up to 4.5°C above pre-industrial levels. To assess potential exposure to novel climatic conditions, the minimum and maximum observed average seasonal values of each climate variable across each (sub)species' geographic range were used to define a climatic envelope. Future climate projections were then compared against these bounds to determine where novel climates may emerge under various warming scenarios – although it is important to note that these climates are novel relative to the current geographic ranges of giraffe populations and may not fall outside the range of broader climatic conditions historically experienced prior to any range contractions. Finally, as a precursor to later chapters which explore non-climatic anthropogenic impacts on giraffe, observed land-use changes and projections of human population were described for each giraffe range.

3.2 Methods

All analyses in this chapter were carried out in R 4.2.2 (R Core Team, 2022).

3.2.1 Study extent

All analyses in this chapter were carried out over the current geographic ranges of each giraffe species and subspecies, using range maps obtained from O'Connor *et al.* (2019) (Figure 3.1). The species' ranges vary in size: Southern giraffe have the largest range area at 731,350 km², followed by Masai giraffe (424,154 km²), Reticulated giraffe (349,831 km²), and then Northern giraffe have the smallest range area at 211,712 km² (O'Connor *et al.*, 2019). Both the Northern and Reticulated giraffe had areas of range labelled as 'possible', which were not supported by empirical data. These areas were removed from the analysis to focus on areas of confirmed giraffe ranges. Large range polygons, such as those for Masai and Reticulated giraffe, were divided into smaller polygons for the analysis to avoid averages over large areas masking finer-scale variation. These polygons were divided based on climatic similarity, ensuring that smaller polygons represented areas of relatively similar environmental conditions, if possible. One circular 200 km² range polygon was also added to the analysis after a sighting of giraffe in Koundjourou, Chad (GCF, 2022). This resulted in a total of 109 range polygons used in the analysis.

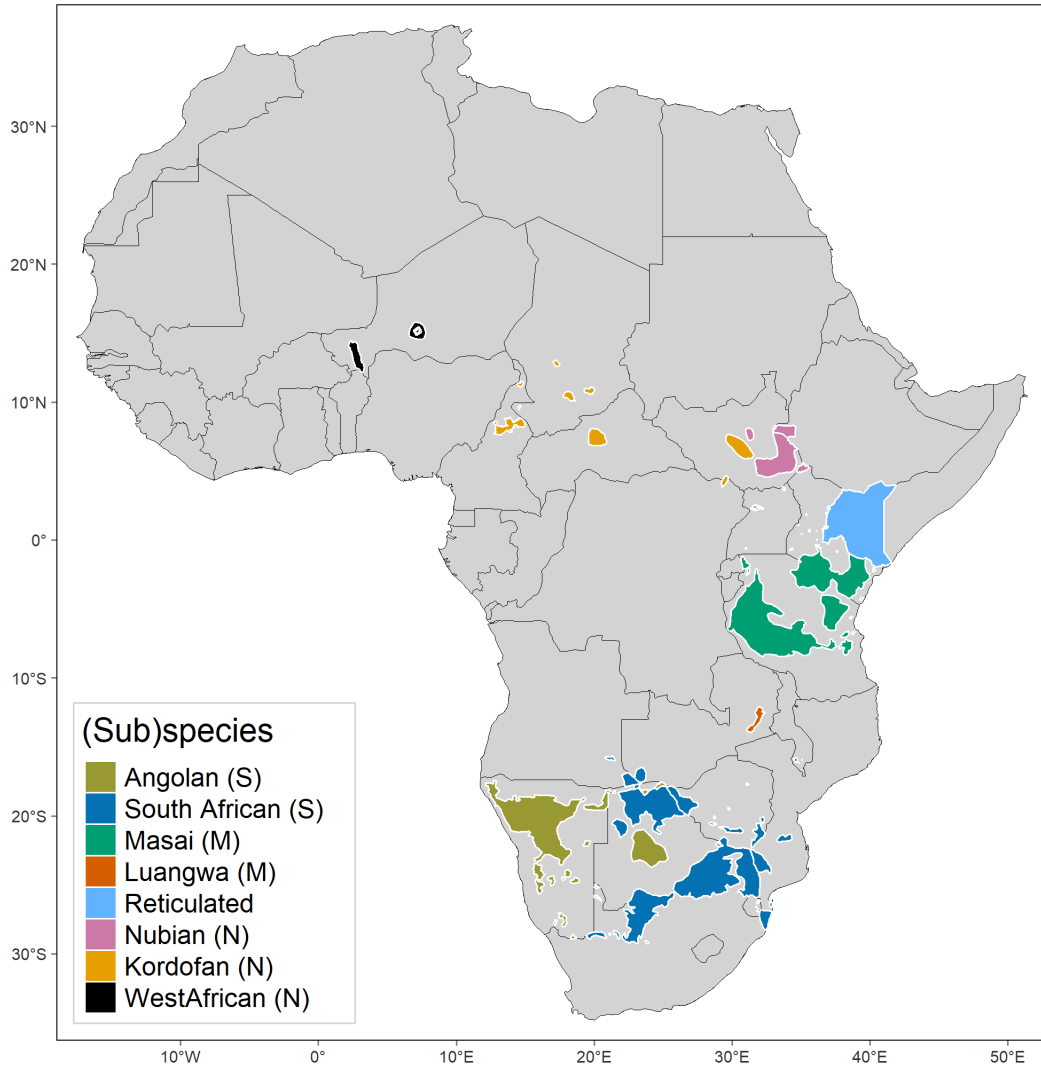


Figure 3.1: The range maps used in this chapter for the species and subspecies of giraffe. Ranges with bracketed letters indicate subspecies belonging to: (S) Southern giraffe, (N) Northern giraffe, and (M) Masai giraffe. Range polygons are from O'Connor *et al.* (2019) with slight modification – areas of unconfirmed but 'possible' range have been removed, and the designation of two Northern giraffe polygons has been updated to different subspecies following more recently available information.

3.2.2 Data

Seasonal temperature and precipitation variables

Seasonal temperature and precipitation data used in this chapter are for the observed time period of 1961-1990 and projected global warming levels of 1.5, 2.0, 2.7, 3.2, and 4.5°C above the pre-industrial levels (1850-1900). The observed data is from the CRU TS 3.24 dataset (Harris *et al.*, 2014) and projected data are ClimGEN outputs (Osborn *et al.*, 2016) derived from 21 CMIP5 general circulation models (GCMs). ClimGEN applies a

pattern-scaling technique to downscale these GCMs to a finer spatial resolution, producing outputs at monthly time intervals. The temperature and precipitation variables examined are seasonal mean, minimum, and maximum temperature, precipitation, cloud cover, and number of wet days. For projections of precipitation, there can be disagreements in the direction of change between GCMs, where some models may project a drying climate and others project a wetting climate. For this reason, range reports show projected precipitation as a median across GCMs, as well as the median value for 'dry' GCMs and 'wet' GCMs.

All climate data was produced at a 0.5×0.5 degree spatial resolution, but was resampled to ~1 km resolution using the nearest-neighbour method in order to better capture small geographical range areas. This approach preserves the original climate values while subdividing each coarse grid cell into smaller cells, allowing giraffe range polygons that fall within, or span only part of, a 0.5 degree grid cell to be included in the analysis. Temperature and precipitation variables are summarised as averages over four seasons: December-January-February (DJF), March-April-May (MAM); June-July-August (JJA); and September-October-November (SON). These seasonal averages were calculated by averaging the values of the three relevant months. As ClimGEN produces monthly outputs, it was not possible to create the seasonal averages from individual daily values.

Drought and waterlogging

Drought and waterlogging data used in this research were obtained from Price *et al.* (2022), and span the 1961-1990 observed climate and global warming levels of 1.5, 2, 2.5, 3, 3.5, and 4°C. The data is based on the Standardised Precipitation-Evapotranspiration Index for 12-month running means (SPEI12; Vicente-Serrano *et al.*, 2010), which accounts for both precipitation and temperature changes. Price *et al.* (2022) calculated SPEI values following the methodology from Vicente-Serrano *et al.* (2010), finding the 12-month running means in the difference between monthly precipitation and potential evapotranspiration (PET) of the observed 1961-1990 climate data and fitting a log-logistic distribution. The resulting probability distributions were then used to calculate observed and projected SPEI12 values, and the maximum consecutive months (MCM) of drought (negative SPEI12) and waterlogging (positive SPEI12) across the 30-year periods each global warming level was centred on. This MCM metric indicates how the duration of drought and waterlogging

events may change under different global warming levels. While this metric captures changes in the longest-lasting events, it does not account for the frequency or duration of shorter events. Nevertheless, it provides valuable insight into how the most prolonged and severe events might intensify under climate change. In this study, MCM values were examined for four SPEI12 thresholds: -1.5 (severe drought), -2 (extreme drought), and opposing levels of 1.5 (severe waterlogging), and 2 (extreme waterlogging).

Human population and land cover data

Population data used in this analysis are from the Center for Integrated Earth System Information (CIESIN) for SSP2 (a ‘middle of the road’ scenario where socioeconomic trends follow generally the same pattern as historic trends) (Gao, 2020). This data is at 1 km resolution and has values for 2010 through to 2100 for each 10-year increment. Human population data was summed across each giraffe population’s geographic range, as well as within an additional 15 km buffer zone. The land cover data is from the European Space Agency Climate Change Initiative (ESA CCI) Land Cover project (ESA, 2017) and Copernicus Climate Change Service (C3S, 2019) and is based on the UN Land Cover Classification System (LCCS). This data has a 300 m resolution and shows land cover for 1992 and 2022. The percentage cover of each land cover class across the (sub)species’ geographic range was calculated at both time periods.

3.2.3 Cluster analysis

As an initial exploratory analysis, agglomerative hierarchical clustering was used to examine the climatic similarity between giraffe populations in the observed timeframe (1961-1990) and at a projected global warming level of 3.2°C. Hierarchical clustering has been suggested as a good method for investigating the climatic relationships between regions or groups (Kreft and Jetz, 2010) and has been used by some as a precursor to species distribution modelling to identify ecologically distinct groups (Lorestani *et al.*, 2022). The average value across each giraffe range polygon was extracted for maximum, minimum, and average temperature and precipitation, for each of the four seasons. To account for the possible impact of seasonal timing (i.e., ranges on either sides of the equator having similar climate but at different times of the year), values were then taken for the season with the highest maximum temperature, the season with the lowest

minimum temperature, the multi-season average of average temperature, and the season with the highest and lowest precipitation. This increases comparability of the climate between giraffe ranges and results in a reduced input of five variables as opposed to 16. Cluster analyses were performed in R 4.2.2 (R Core Team, 2022) using the *cluster* package (Maechler *et al.*, 2022) and the function ‘agnes’. Input variables were standardised prior to the cluster analysis, to ensure large precipitation values did not skew the analysis. The Euclidean distance metric was used, and Ward’s linkage method was used, which minimises variance between the clusters.

3.2.4 Range reports

A range report was produced for each giraffe range polygon, where average values were extracted and summarised for each of the observed and projected climate variables (minimum, maximum and average temperature, precipitation, drought, and waterlogging), observed land use change, and observed and projected human population count. These range reports can be found on the GiraffeClim application (detailed in Chapter 6).

To condense the information from these range reports into a useful narrative for this chapter, the results shown below are the median, minimum, and maximum values from across each (sub)species geographic range. Four key climate variables were selected: maximum temperature, minimum temperature, precipitation, and maximum consecutive months of drought and waterlogging. For projections of precipitation, the median GCM ensemble value was used, whilst in the individual range reports, precipitation is also shown separately for groups of GCMs projecting wetting or drying trends.

3.2.5 Novel climate

Two assessments were carried out to understand the exposure of each giraffe (sub)species to novel climatic conditions at projected warming levels. The first assessment examined areas where future climate is projected to be outside the bounds of that experienced across the (sub)species’ current geographic range in the observed (1961-1990) climate period. To achieve this, upper and lower limits across each (sub)species’ geographic range were extracted for observed average seasonal maximum temperature, minimum temperature,

and precipitation. At projected global warming levels of 2 and 3.2°C, areas which exceeded these (sub)species-specific climate bounds for any of the climate variables or seasons were classed as novel climate.

The second assessment of novel climate presented in this chapter was cell-specific, focusing on seasonal minimum and maximum temperatures at each global warming level. Minimum temperature is examined here because increases in the lowest temperatures within a season may reduce opportunities for giraffe to thermoregulate and to engage in behaviours, such as movement, that are often concentrated during cooler periods of the day and night (Fennessy, 2009). In this analysis, a cell was considered to experience novel climate if the projected mean minimum or maximum temperature at a given warming level exceeded two standard deviations from the 1961–1990 baseline climate (equivalent to a 1 in 20-year event). The percentage of each (sub)species' geographic range projected to be exposed to these novel climates was then calculated. Precipitation was excluded from this analysis due to its high variability, which reduces the likelihood of exceeding the two-standard-deviation threshold in future scenarios. These two methods capture climates which are novel according to the current species' geographic range but may not capture the breadth of climates the species has historically been exposed to, due to population declines and range contractions.

3.3 Results

3.3.1 Cluster analysis

The Southern giraffe ranges (Angolan and South African subspecies) are almost completely separated from all other (sub)species in the cluster analysis (Figure 3.2), suggesting they could be adapted to different climates. Only six South African giraffe ranges are found outside this Southern giraffe cluster, and these ranges correspond to the easternmost ranges of South African giraffe, in Malawi and Mozambique. There is a cluster of Kordofan, West African, and Nubian ranges which have similar climates, and only seven ranges (one Kordofan, six Nubian) which are more clustered with Masai and Reticulated ranges. Reticulated and Masai giraffe are clustered together, alongside some of the other (sub)species ranges.

When the same cluster analysis is performed with climate data projected to 3.2°C of global warming, there are slight differences in clustering. Mainly, the South African and Angolan range cluster is removed from all other ranges by the highest-level split – again, excluding six of the easternmost South African giraffe ranges (Figure 3.3). West African ranges become more closely clustered with each other, whilst many Nubian and Kordofan ranges become less closely clustered (Figure 3.3).

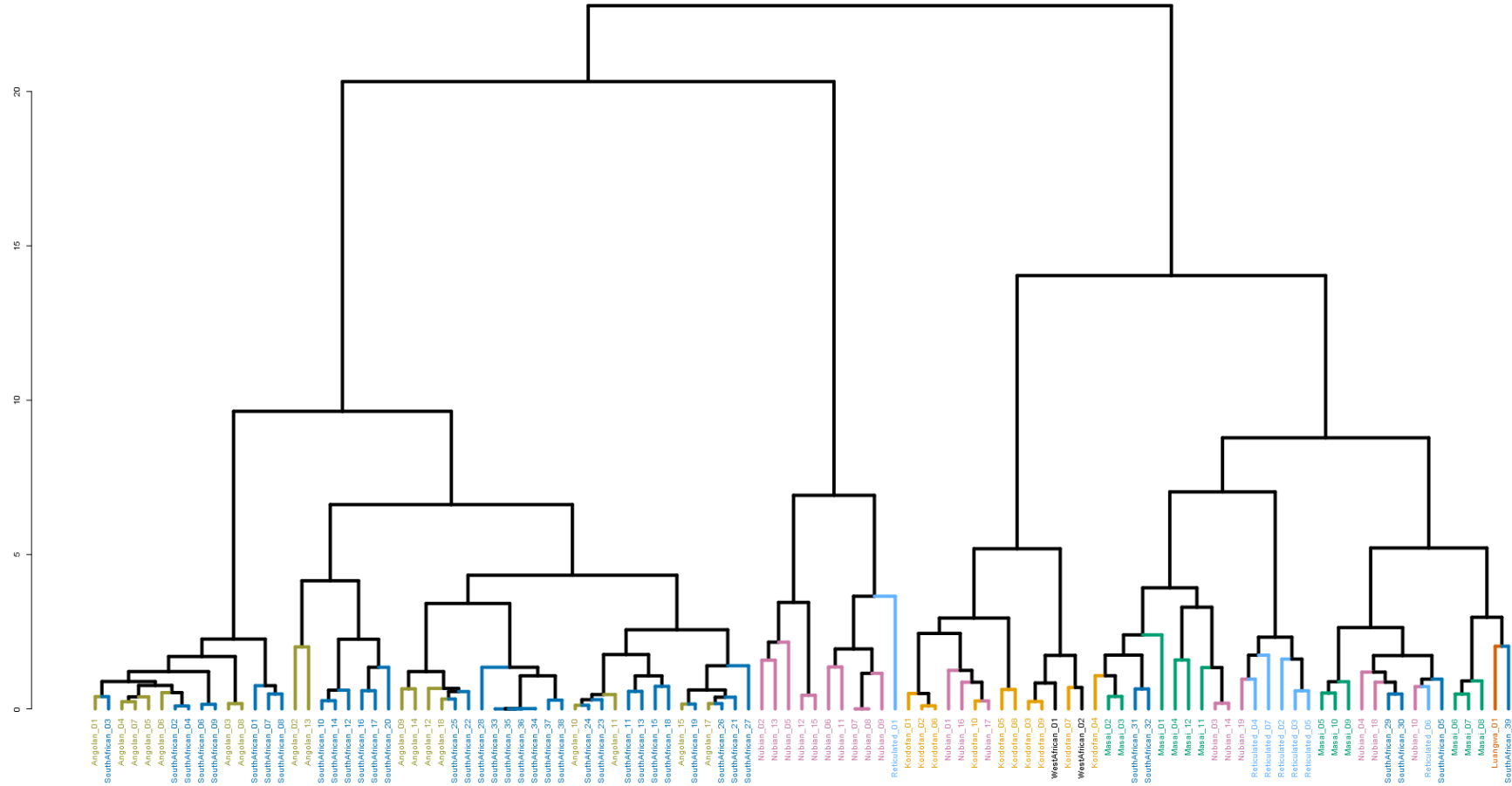


Figure 3.2: Agglomerative hierarchical cluster analysis showing the climatic similarity of species' ranges for the observed climate (1961-1990). The y-axis shows the Euclidean distance, and the linkage method used was Ward's method, which minimises the variance within clusters.

3.3.2 Range report summaries

Average seasonal maximum temperature

As a median across the (sub)species' geographic ranges, West African giraffe were exposed to the hottest average seasonal maximum temperature in the observed climate period, at 40°C for the March-May season (Table 3.1). The eight hottest median range values for the seasonal observed climate all belong to subspecies of Northern giraffe. The Angolan giraffe was exposed to the coldest observed seasonal maximum temperature at 24.4°C for June-August as a median across its range. The Masai giraffe is the only (sub)species with a median value below 30°C for all seasons in the observed climate period.

All species and subspecies are projected to see an increase in the seasonal average maximum temperature at increasing global warming levels (Table 3.1). At 2.0°C warming, all species' geographic ranges are projected to experience an increase in maximum temperature of at least 1.2°C, regardless of season. Under the highest warming scenario of 4.5°C, all species ranges are projected to experience an increase in average seasonal maximum temperature of at least 3.4°C, regardless of the season. Southern giraffe (South African and Angolan subspecies) are exposed to the highest seasonal increases in maximum temperature at all projected global warming levels compared to all other subspecies. Reticulated giraffe, as a median across their geographic range, are projected to be exposed to the smallest increase in maximum temperature across seasons, at all global warming levels.

Table 3.1: Observed and projected change in average seasonal maximum temperature at five global warming levels, showing the median, minimum and maximum values across the (sub)species' geographic range. Projected values are the ensemble mean from 21 GCMs. Table shading is based on the median value and spans from light to dark red as a comparison of values across all (sub)species.

Species/ subspecies	Season	Observed 1961-1990	Temperature anomaly at specified warming level (°C)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Angolan	DJF	31.9 (20.7-35.4)	1.7 (1.3-1.7)	2.2 (1.6-2.3)	3.3 (2.5-3.4)	3.9 (3-4.1)	5.9 (4.4-6.1)
	MAM	28.1 (19.6-30.7)	1.8 (1.3-1.8)	2.3 (1.7-2.4)	3.5 (2.6-3.7)	4.2 (3.1-4.4)	6.2 (4.6-6.5)
	JJA	24.4 (16.1-28.1)	1.7 (1.4-1.8)	2.2 (1.8-2.4)	3.4 (2.8-3.6)	4 (3.3-4.3)	6 (5-6.4)
	SON	31.5 (17.6-34.7)	1.8 (1.2-1.9)	2.4 (1.6-2.5)	3.6 (2.5-3.8)	4.3 (2.9-4.5)	6.4 (4.4-6.8)
Kordofan	DJF	34.7 (31.2-37.5)	1.3 (1.3-1.4)	1.7 (1.7-1.8)	2.6 (2.5-2.8)	3.1 (3-3.3)	4.6 (4.5-4.9)
	MAM	34.9 (31-41.1)	1.3 (1.3-1.4)	1.8 (1.7-1.9)	2.7 (2.6-2.9)	3.2 (3.1-3.4)	4.8 (4.6-5.1)
	JJA	29.6 (27.1-35.7)	1.3 (1.3-1.4)	1.7 (1.7-1.9)	2.6 (2.6-2.9)	3.1 (3-3.4)	4.7 (4.5-5)
	SON	31.5 (28.9-36.3)	1.2 (1.1-1.3)	1.6 (1.5-1.8)	2.4 (2.3-2.7)	2.8 (2.7-3.2)	4.2 (4.1-4.7)
Luangwa	DJF	29.2 (27.8-30)	1.5 (1.5-1.5)	1.9 (1.9-2)	2.9 (2.9-3)	3.5 (3.5-3.5)	5.2 (5.2-5.3)
	MAM	28.7 (27.4-29.6)	1.4 (1.4-1.5)	1.9 (1.9-1.9)	2.9 (2.9-2.9)	3.5 (3.4-3.5)	5.2 (5.1-5.2)
	JJA	27.1 (25.6-28)	1.4 (1.4-1.4)	1.9 (1.8-1.9)	2.8 (2.8-2.9)	3.3 (3.3-3.4)	5 (4.9-5.1)
	SON	32.4 (31.3-33.5)	1.6 (1.6-1.6)	2.1 (2.1-2.2)	3.2 (3.2-3.3)	3.8 (3.8-3.9)	5.7 (5.6-5.8)
Masai	DJF	27.8 (23.3-34.7)	1.2 (1-1.3)	1.6 (1.2-1.8)	2.4 (1.9-2.7)	2.8 (2.3-3.2)	4.2 (3.4-4.7)
	MAM	27.5 (22.8-34.8)	1.3 (1-1.4)	1.7 (1.4-1.8)	2.6 (2.1-2.7)	3 (2.5-3.2)	4.5 (3.7-4.8)
	JJA	27 (20.3-31.6)	1.3 (1-1.5)	1.8 (1.3-2)	2.7 (2-3)	3.2 (2.4-3.5)	4.8 (3.6-5.3)
	SON	29.3 (21.8-33.6)	1.4 (1-1.5)	1.8 (1.2-2)	2.7 (1.9-3)	3.2 (2.3-3.5)	4.8 (3.4-5.3)
Nubian	DJF	36.3 (23.3-37.2)	1.2 (1.0-1.3)	1.6 (1.3-1.7)	2.4 (2-2.6)	2.9 (2.4-3.1)	4.3 (3.6-4.6)
	MAM	35.5 (22.8-37.1)	1.2 (1.1-1.3)	1.6 (1.5-1.8)	2.5 (2.3-2.7)	3 (2.7-3.2)	4.4 (4.1-4.7)
	JJA	31.5 (20.3-32.1)	1.4 (1.2-1.5)	1.8 (1.6-1.9)	2.7 (2.4-2.9)	3.2 (2.8-3.5)	4.8 (4.2-5.2)
	SON	33.3 (21.8-34.1)	1.2 (1.1-1.3)	1.6 (1.5-1.7)	2.4 (2.2-2.6)	2.9 (2.6-3.1)	4.3 (3.9-4.6)

Species/ subspecies	Season	Observed 1961-1990	Temperature anomaly at specified warming level (°C)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Reticulated	DJF	33.5 (20-36)	1.1 (1.0-1.1)	1.4 (1.3-1.5)	2.1 (2-2.2)	2.5 (2.4-2.7)	3.8 (3.5-4)
	MAM	33.5 (19.5-35.9)	1.2 (1.0-1.3)	1.6 (1.4-1.7)	2.4 (2.1-2.5)	2.8 (2.5-3)	4.2 (3.7-4.4)
	JJA	30.6 (16.2-33.1)	1.2 (1.0-1.3)	1.5 (1.3-1.7)	2.3 (2-2.5)	2.8 (2.3-3)	4.1 (3.5-4.5)
	SON	32.3 (18.4-34.6)	1.1 (1.0-1.2)	1.4 (1.3-1.6)	2.2 (1.9-2.4)	2.6 (2.3-2.8)	3.9 (3.4-4.2)
South African	DJF	31.5 (24.2-35.6)	1.6 (1.0-1.8)	2.1 (1.3-2.3)	3.1 (2-3.5)	3.7 (2.3-4.1)	5.6 (3.5-6.1)
	MAM	28.5 (21.8-30.5)	1.7 (1.0-1.8)	2.2 (1.3-2.4)	3.3 (2-3.7)	4 (2.4-4.3)	5.9 (3.5-6.5)
	JJA	25 (18.3-27.6)	1.6 (1.0-1.8)	2.1 (1.3-2.4)	3.2 (2-3.6)	3.8 (2.4-4.3)	5.6 (3.6-6.4)
	SON	30.2 (22.8-33.9)	1.8 (1.0-1.9)	2.4 (1.3-2.5)	3.7 (2-3.9)	4.3 (2.4-4.6)	6.5 (3.6-6.8)
West African	DJF	33.6 (30.6-34.7)	1.4 (1.4-1.5)	1.9 (1.8-1.9)	2.8 (2.8-2.9)	3.4 (3.3-3.4)	5 (4.9-5.1)
	MAM	40 (39.1-40.4)	1.5 (1.4-1.5)	1.9 (1.8-2)	2.9 (2.8-3)	3.5 (3.3-3.6)	5.2 (5-5.3)
	JJA	35.8 (33-37.9)	1.4 (1.4-1.4)	1.8 (1.8-1.9)	2.8 (2.7-2.8)	3.3 (3.2-3.3)	4.9 (4.8-5)
	SON	36 (34.8-36.8)	1.3 (1.3-1.5)	1.8 (1.7-1.9)	2.7 (2.5-2.9)	3.2 (3-3.5)	4.8 (4.5-5.2)

Average seasonal minimum temperature

In the observed climate period, West African giraffe were exposed to the hottest seasonal minimum temperature at 25.3°C as a median across their geographic range for the March-May season (Table 3.2). Angolan and South African giraffe are the only (sub)species where the median value across their geographic range is below 10°C in any season; for the June-August season, Angolan giraffe were exposed to a median value of 7.0°C, and South African giraffe were exposed to a median value of 7.1°C.

All species and subspecies are projected to be exposed to increasing average seasonal minimum temperatures with higher global warming levels (Table 3.2). At 2.0°C warming, all (sub)species are projected to experience an increase of at least 1.2°C across their geographic ranges in all seasons. Warming trends are consistent across species, although Masai and Reticulated giraffe are exposed to smaller median increases than other (sub)species at each warming level. At the highest level of global warming explored, the largest temperature increase across all species and seasons is in the West African giraffe's

range, with an increase of 6.4°C in the September-November season.

Table 3.2: Observed and projected change in average seasonal minimum temperature at five global warming levels, showing the median, minimum and maximum values across the (sub)species' geographic range. Projected values are the ensemble mean from 21 GCMs. Light to dark red shading is based on the median value as a comparison of values across all (sub)species.

Species/ subspecies	Season	Observed	Temperature anomaly at specified global warming level (°C)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Angolan	DJF	17.1 (13.8-19.8)	1.5 (1.3-1.6)	2 (1.7-2.1)	3 (2.5-3.2)	3.6 (3-3.8)	5.3 (4.5-5.8)
	MAM	13.5 (11.3-15.9)	1.6 (1.3-1.7)	2.1 (1.7-2.2)	3.2 (2.5-3.4)	3.7 (3-4)	5.6 (4.5-5.9)
	JJA	7 (2.6-12.6)	1.6 (1.2-1.7)	2.1 (1.7-2.2)	3.2 (2.5-3.3)	3.8 (3-3.9)	5.6 (4.4-5.8)
	SON	13.7 (10-18.5)	1.7 (1.3-1.8)	2.2 (1.7-2.4)	3.4 (2.5-3.6)	4 (3-4.2)	5.9 (4.5-6.3)
Kordofan	DJF	16.7 (13.7-18.9)	1.7 (1.5-1.7)	2.2 (2.0-2.2)	3.3 (3-3.3)	3.9 (3.6-3.9)	5.8 (5.4-5.9)
	MAM	22.1 (19.1-24.8)	1.4 (1.4-1.5)	1.9 (1.8-2.1)	2.9 (2.8-3.1)	3.4 (3.3-3.7)	5.1 (4.9-5.5)
	JJA	20.4 (17.8-23.9)	1.4 (1.3-1.5)	1.8 (1.7-1.9)	2.7 (2.6-2.9)	3.2 (3.1-3.5)	4.8 (4.6-5.2)
	SON	19 (16.6-21)	1.5 (1.4-1.7)	2 (1.9-2.2)	3 (2.8-3.4)	3.6 (3.3-4)	5.3 (5-6)
Luangwa	DJF	19.1 (17.6-19.6)	1.4 (1.4-1.4)	1.8 (1.8-1.9)	2.8 (2.8-2.8)	3.3 (3.3-3.3)	4.9 (4.9-5)
	MAM	16.3 (15.1-17)	1.4 (1.4-1.5)	1.9 (1.9-2)	2.9 (2.9-3)	3.4 (3.4-3.5)	5.1 (5.1-5.2)
	JJA	11.1 (10.2-11.8)	1.5 (1.4-1.5)	1.9 (1.9-1.9)	2.9 (2.9-2.9)	3.5 (3.4-3.5)	5.2 (5.1-5.2)
	SON	17.9 (16.5-18.4)	1.5 (1.5-1.6)	2 (2.0-2.1)	3.1 (3.1-3.1)	3.7 (3.6-3.7)	5.5 (5.4-5.5)
Masai	DJF	17.2 (7.8-23.3)	1.3 (1.1-1.4)	1.7 (1.4-1.8)	2.6 (2.2-2.8)	3.1 (2.6-3.3)	4.7 (3.8-5)
	MAM	16.9 (9.4-23.9)	1.3 (1.1-1.5)	1.8 (1.4-1.9)	2.7 (2.2-2.9)	3.2 (2.6-3.5)	4.8 (3.9-5.1)
	JJA	13.8 (7.6-22.1)	1.4 (1-1.6)	1.8 (1.3-2.1)	2.8 (2-3.2)	3.3 (2.4-3.8)	4.9 (3.5-5.7)
	SON	17 (7.6-22.6)	1.3 (1-1.5)	1.8 (1.3-1.9)	2.7 (2-2.9)	3.1 (2.3-3.4)	4.7 (3.5-5.1)
Nubian	DJF	19.5 (7.8-20.5)	1.6 (1.4-1.7)	2.1 (1.8-2.2)	3.2 (2.7-3.3)	3.8 (3.3-3.9)	5.7 (4.9-5.8)
	MAM	21.8 (9.4-23.2)	1.4 (1.3-1.5)	1.9 (1.7-1.9)	2.9 (2.6-3)	3.4 (3.1-3.5)	5.1 (4.6-5.2)
	JJA	20.6 (7.6-21.6)	1.5 (1.3-1.6)	1.9 (1.7-2.1)	2.9 (2.6-3.2)	3.5 (3-3.7)	5.2 (4.5-5.6)
	SON	20.1 (7.6-21.1)	1.5 (1.2-1.5)	1.9 (1.6-2)	3 (2.4-3)	3.5 (2.9-3.6)	5.2 (4.3-5.4)

Species/ subspecies	Season	Observed	Temperature anomaly at specified global warming level (°C)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Reticulated	DJF	21	1.4	1.9	2.8	3.4	5
		(7-23.9)	(1.1-1.6)	(1.4-2)	(2.2-3.1)	(2.6-3.7)	(3.9-5.4)
	MAM	22.2	1.4	1.8	2.8	3.3	4.9
		(8.6-24.8)	(1.1-1.5)	(1.4-2)	(2.2-3)	(2.5-3.5)	(3.8-5.2)
	JJA	20	1.3	1.7	2.6	3	4.5
South African	DJF	(7.1-22.6)	(1-1.4)	(1.3-1.9)	(2-2.8)	(2.3-3.3)	(3.5-5)
		21	1.3	1.7	2.5	3	4.5
	MAM	(7.8-23.6)	(1-1.4)	(1.3-1.8)	(2-2.8)	(2.3-3.3)	(3.5-4.9)
		19.1	1.5	1.9	2.9	3.5	5.2
	JJA	(13.2-22.6)	(1-1.7)	(1.3-2.2)	(1.9-3.3)	(2.3-3.9)	(3.4-5.9)
West African	DJF	14.1	1.6	2.1	3.1	3.7	5.5
		(8.8-19.7)	(1-1.7)	(1.3-2.2)	(2-3.4)	(2.3-4)	(3.5-5.9)
	MAM	7.1	1.5	2	3	3.5	5.3
		(1-15.2)	(1-1.6)	(1.3-2.2)	(2-3.3)	(2.3-3.9)	(3.5-5.8)
	JJA	15.9	1.6	2.2	3.3	3.9	5.8
Kordofan	DJF	(9.3-20.4)	(0.9-1.8)	(1.2-2.4)	(1.9-3.6)	(2.2-4.3)	(3.3-6.3)
		16.9	1.7	2.1	3.3	3.9	5.8
	MAM	(13.7-18.1)	(1.6-1.7)	(2.1-2.2)	(3.2-3.3)	(3.8-4)	(5.7-5.9)
		25.3	1.6	2.1	3.2	3.8	5.7
	JJA	(23.4-25.8)	(1.5-1.7)	(2-2.2)	(3-3.3)	(3.6-3.9)	(5.3-5.9)
Nubian	DJF	24.2	1.4	1.8	2.8	3.3	4.9
		(23.2-25.2)	(1.3-1.5)	(1.7-2)	(2.6-3.1)	(3.1-3.6)	(4.6-5.4)
	MAM	21.4	1.7	2.3	3.5	4.1	6.2
		(21-22.4)	(1.6-1.8)	(2.2-2.4)	(3.3-3.6)	(3.9-4.3)	(5.8-6.4)
	JJA	(21-22.4)	(1.6-1.8)	(2.2-2.4)	(3.3-3.6)	(3.9-4.3)	(5.8-6.4)

Seasonal precipitation

Observed (1961-1990) precipitation values show large differences between (sub)species and seasons (Table 3.3). Similarly, projections of precipitation change at increasing global warming levels show differing wetting and drying trends across (sub)species and seasons (Table 3.3). Angolan and Luangwa giraffe are the only (sub)species where the entire geographic range is projected to dry across all seasons and warming levels. The median precipitation change across the South African giraffe's geographic range shows a decrease in precipitation, although some parts of the range are projected to see an increase in precipitation. The three Northern giraffe subspecies (Kordofan, Nubian, and West African giraffe) are the only geographic ranges where the median value shows a projected increase in precipitation across all warming levels and seasons. It is important to note however, that these subspecies do have some areas which are projected to dry. Reticulated giraffe are exposed to the largest absolute increase in precipitation across any giraffe geographic range, where projections show an increase of up to 31.7 mm at 2°C (March-May), and up to

72.1 mm at the highest warming level of 4.5°C (March-May). The largest decrease in precipitation across (sub)species and seasons is in the Masai giraffe's geographic range for June-August, with -11.3 mm at 2°C and -22.0 mm at 4.5°C.

Table 3.3: Observed and projected change in average seasonal precipitation at five global warming levels. Projected values are the median ensemble value of the 21 GCMs. Values show the median, minimum, and maximum value across each (sub)species' geographic range, and cells are coloured based on the median value to represent either an increase (blue) or decrease (orange) in precipitation over the projected warming levels.

Species/ subspecies	Season	Observed (mm)	Precipitation anomaly at warming level (mm)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Angolan	DJF	62.5	-2.6	-3.3	-4.7	-5.5	-7.5
		(0.9, 142.9)	(-4.5, -0.2)	(-5.8, -0.3)	(-8.5, -0.4)	(-9.9, -0.4)	(-13.9, -0.3)
	MAM	29	-1.8	-2.4	-3.4	-3.8	-5.1
		(1.7, 58)	(-2.7, -0.3)	(-3.5, -0.4)	(-5, -0.5)	(-5.7, -0.6)	(-7.7, -0.7)
	JJA	0	-0.3	-0.5	-0.7	-0.7	-1
Kordofan	DJF	(0, 10.9)	(-1.3, -0.1)	(-1.7, -0.2)	(-2.4, -0.2)	(-2.8, -0.3)	(-3.8, -0.4)
		10.8	-1.4	-1.8	-2.5	-2.8	-3.7
	MAM	(0, 30.4)	(-3.8, -0.1)	(-4.9, -0.1)	(-7, -0.1)	(-8, -0.1)	(-10.8, -0.2)
		0	0.1	0.2	0.3	0.4	0.6
	JJA	(0, 24)	(0, 4.5)	(0, 5.8)	(0, 8.3)	(0, 9.6)	(0, 13.4)
Luangwa	DJF	75.9	1.5	2.1	3.2	3.8	5.8
		(4.8, 140.4)	(0.3, 2.6)	(0.3, 3.5)	(0.5, 5.4)	(0.6, 6.4)	(1, 9.4)
	MAM	202.2	5.7	7.7	11.8	14	20.9
		(92.8, 241.8)	(-2.2, 10.3)	(-2.9, 13.9)	(-4.1, 20.9)	(-4.6, 24.7)	(-6.1, 35.1)
	JJA	117.2	5.6	7.6	11.6	13.7	20.3
Masai	DJF	(18.8, 158.1)	(3, 8.2)	(4, 11)	(6.3, 16.6)	(7.5, 19.7)	(11.5, 29.2)
		232.9	-2.4	-2.8	-3.3	-3.3	-2.6
	MAM	(216.3, 236.4)	(-2.9, -2.1)	(-3.6, -2.5)	(-4.3, -2.8)	(-4.5, -2.8)	(-4.1, -1.8)
		64.6	-1.6	-1.9	-2.2	-2.3	-1.9
	JJA	(57.2, 69.2)	(-1.8, -1.2)	(-2.2, -1.4)	(-2.6, -1.5)	(-2.7, -1.5)	(-2.5, -0.9)
Angolan	DJF	0	-0.3	-0.3	-0.5	-0.6	-0.8
		(0, 0)	(-0.3, -0.2)	(-0.5, -0.3)	(-0.6, -0.4)	(-0.8, -0.5)	(-1.1, -0.8)
	MAM	20.8	-2.4	-3.1	-4.5	-5.2	-7.1
		(16.2, 32.2)	(-3.2, -2.2)	(-4.2, -2.8)	(-6.1, -4.1)	(-7, -4.7)	(-9.6, -6.4)
	JJA	131.8	5.3	7.1	11.1	13.3	20.1
Kordofan	DJF	(15.1, 192.3)	(0, 14.6)	(0.1, 19.2)	(0.4, 28.6)	(0.7, 33.6)	(1.8, 47.4)
		109.2	1.5	2.2	3.8	4.6	7.4
	MAM	(43.1, 286)	(-1.4, 10.9)	(-1.6, 14.8)	(-1.7, 22.4)	(-1.6, 25.9)	(-0.8, 36.7)
		2.5	-0.5	-0.7	-0.9	-1.1	-1.5
	JJA	(0, 114.9)	(-8.8, 0.7)	(-11.3, 1)	(-15.4, 1.6)	(-17.3, 2)	(-22, 3.1)
Luangwa	DJF	42.9	-1.3	-1.7	-2.4	-2.8	-3.7
		(9.4, 121.8)	(-4.7, 5.3)	(-6.2, 7.2)	(-8.8, 11.1)	(-10, 13.2)	(-13.3, 19.8)
	MAM	42.9	-1.3	-1.7	-2.4	-2.8	-3.7
		(9.4, 121.8)	(-4.7, 5.3)	(-6.2, 7.2)	(-8.8, 11.1)	(-10, 13.2)	(-13.3, 19.8)
	JJA	42.9	-1.3	-1.7	-2.4	-2.8	-3.7

Species/ subspecies	Season	Observed (mm)	Precipitation anomaly at warming level (mm)				
			1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Nubian	DJF	7.8	2.7	3.4	4.7	5.4	7.3
		(0, 98.4)	(0.2, 17.2)	(0.2, 22.4)	(0.3, 32.6)	(0.4, 38.1)	(0.6, 53.5)
	MAM	68.6	2.7	3.7	5.7	6.7	9.5
		(41.5, 200.7)	(0.3, 18)	(0.5, 24.4)	(0.7, 35.9)	(0.9, 41.6)	(1.5, 58.6)
	JJA	129.5	1.7	2.4	3.8	4.5	7
Reticulated	DJF	(9.6, 205.5)	(-2.4, 4.8)	(-2.9, 6.5)	(-3.6, 10)	(-4, 11.9)	(-5, 17.8)
		79.7	3.3	4.5	6.9	8.2	11.9
	MAM	(35.1, 138)	(1.9, 9.2)	(2.7, 12.4)	(4.3, 18.9)	(5.2, 22.1)	(8.2, 31.3)
		22.1	8	10.2	14.3	16.4	22.1
	JJA	(3.7, 59)	(2, 18.9)	(2.6, 24.7)	(3.7, 35.2)	(4.2, 40.5)	(5.7, 54.8)
South African	DJF	81.3	8.1	10.6	15.3	17.6	24.3
		(43.1, 279)	(-0.7, 24.2)	(-0.7, 31.7)	(-0.7, 45.3)	(-0.5, 52.4)	(0.3, 72.1)
	MAM	2	-0.1	-0.1	-0.1	-0.1	-0.1
		(0, 112.6)	(-7.4, 2.2)	(-9.4, 3)	(-12.9, 4.3)	(-14.5, 5)	(-18.5, 7.4)
	JJA	42.6	4.1	5.5	8.5	10.1	15
West African	DJF	(27.8, 161.5)	(-0.2, 12.6)	(-0.1, 17)	(0.3, 26)	(0.6, 30.6)	(1.8, 44.5)
		88.6	-1.3	-1.7	-2.3	-2.6	-3.3
	MAM	(7.8, 232.2)	(-4.6, 3.3)	(-6, 4.4)	(-8.8, 6.8)	(-10.3, 8.2)	(-14.4, 12.5)
		32	-1.8	-2.4	-3.3	-3.8	-5.2
	JJA	(10.8, 109)	(-3.8, -0.5)	(-4.8, -0.6)	(-6.8, -0.8)	(-7.8, -0.9)	(-10.5, -1.2)
Reticulated	DJF	1.9	-0.5	-0.7	-1	-1.2	-1.6
		(0, 54.9)	(-5, -0.2)	(-6.5, -0.2)	(-9.4, -0.3)	(-10.8, -0.3)	(-14.8, -0.4)
	MAM	29.6	-3.3	-4.3	-6.2	-7.1	-9.6
		(3.2, 94.5)	(-7.1, -0.3)	(-9.3, -0.4)	(-13.3, -0.6)	(-15.2, -0.7)	(-20.6, -1)
	JJA	0	0	0	0	0	0
West African	DJF	(0, 0.1)	(0, 0)	(0, 0)	(-0.1, 0.1)	(-0.1, 0.1)	(-0.1, 0.1)
		5.4	0.1	0.1	0.2	0.3	0.5
	MAM	(0.9, 25.8)	(-0.1, 0.3)	(-0.2, 0.4)	(-0.3, 0.6)	(-0.3, 0.7)	(-0.4, 1)
		101.1	3.2	4.3	6.8	8.1	12.3
	JJA	(64.8, 160.6)	(0.8, 10.1)	(1.2, 13.5)	(2.2, 19.9)	(2.8, 23)	(5, 31.8)
Reticulated	DJF	23.2	6.2	8.1	11.8	13.3	18.5
		(7.1, 55)	(4.7, 7.3)	(5.9, 9.8)	(8, 14.7)	(9.1, 17.1)	(12.5, 24.1)
	MAM	101.1	3.2	4.3	6.8	8.1	12.3
		(64.8, 160.6)	(0.8, 10.1)	(1.2, 13.5)	(2.2, 19.9)	(2.8, 23)	(5, 31.8)
	JJA	23.2	6.2	8.1	11.8	13.3	18.5

Drought and waterlogging

In the observed time period, all species were exposed to a median MCM of between 10 and 12 months of SPEI 1.5 (severe waterlogging), and 6-13 months of SPEI -1.5 (severe drought) across their geographic range (Table 3.4). All species are projected to be exposed to an increase in MCM of severe and extreme drought (SPEI12 -1.5 and -2, respectively) at increasing global warming levels, as a median across their geographic range. Angolan giraffe are projected to be exposed to the longest MCM of severe and extreme drought as a median across their geographic range at all warming levels, compared to all other (sub)species. Additionally, all (sub)species except for Reticulated giraffe are projected to be exposed to a longer MCM of severe drought than MCM of severe waterlogging at each warming level.

Table 3.4: The observed and projected maximum consecutive months (MCM) over a 30-year period (centred on the warming level) at the specified SPEI12 level. Cells are coloured based on their median value to represent the MCM of extreme dry (orange) or wet (blue)

Species/ subspecies	SPEI12	Maximum consecutive months of each SPEI level (months)						
		Observed	1.5°C	2°C	2.5°C	3°C	3.5°C	4°C
Angolan	2.0	4	0	0	0	0	0	0
		(0,12)	(0, 7)	(0, 6)	(0, 6)	(0, 5)	(0, 5)	(0, 6)
	1.5	12	8	5	3	2	1	1
		(7,33)	(0, 12)	(0, 11)	(0, 10)	(0, 10)	(0, 10)	(0, 11)
	-1.5	11	23	36	53	70	87	108
(1,21)		(12, 139)	(12, 236)	(13, 315)	(14, 341)	(15, 342)	(18, 349)	
-2.0	2	13	21	31	46	60	79	
	(0,12)	(4, 94)	(7, 203)	(8, 306)	(9, 341)	(10, 341)	(11, 349)	
Kordofan	2.0	2	4	4	5	6	7	7
		(0,12)	(1, 10)	(2, 10)	(2, 10)	(2, 11)	(3, 12)	(3, 13)
	1.5	11	9	10	10	11	12	13
		(4,19)	(5, 18)	(6, 18)	(6, 19)	(6, 19)	(6, 20)	(7, 21)
	-1.5	12	13	15	17	21	24	28
(4,20)		(8, 23)	(10, 30)	(11, 37)	(13, 54)	(16, 63)	(17, 75)	
-2.0	3	6	8	9	11	13	16	
	(0,12)	(2, 12)	(3, 13)	(4, 19)	(6, 29)	(8, 41)	(10, 48)	
Luangwa	2.0	2	1	1	1	1	2	2
		(2,2)	(1, 1)	(1, 2)	(1, 2)	(1, 3)	(1, 3)	(1, 3)
	1.5	10	7	6	5	5	5	5
		(10,12)	(5, 7)	(4, 7)	(4, 6)	(4, 5)	(4, 5)	(4, 5)
	-1.5	6	17	24	40	56	63	70
(4,11)		(17, 20)	(23, 35)	(38, 49)	(51, 57)	(61, 63)	(68, 72)	
-2.0	1	9	15	23	35	50	56	
	(0,2)	(8, 10)	(13, 17)	(21, 31)	(34, 49)	(45, 54)	(54, 58)	
Masai	2.0	4	4	4	4	5	5	5
		(0,12)	(1, 10)	(1, 9)	(1, 11)	(1, 12)	(1, 13)	(2, 15)
	1.5	12	11	11	10	10	10	10
		(6,19)	(4, 17)	(4, 17)	(4, 19)	(4, 20)	(4, 23)	(4, 31)
	-1.5	8	13	17	23	28	32	41
(1,19)		(5, 28)	(5, 41)	(6, 58)	(6, 72)	(7, 85)	(8, 107)	
-2.0	1	6	9	12	16	20	26	
	(0,11)	(0, 20)	(1, 23)	(1, 33)	(2, 52)	(2, 66)	(3, 85)	
Nubian	2.0	3	3	3	3	4	4	5
		(0,10)	(0, 8)	(1, 10)	(1, 17)	(1, 23)	(2, 29)	(2, 35)
	1.5	10	10	10	9	10	10	10
		(6,17)	(2, 17)	(2, 23)	(3, 29)	(3, 39)	(3, 44)	(4, 50)
	-1.5	10	12	13	15	17	19	20
(4,13)		(5, 16)	(6, 20)	(6, 23)	(7, 29)	(8, 34)	(8, 44)	
-2.0	2	4	5	7	8	9	11	
	(0,9)	(0, 10)	(1, 11)	(3, 11)	(3, 13)	(4, 19)	(5, 26)	

Species/ subspecies	SPEI12	Maximum consecutive months of each SPEI level (months)						
		Observed	1.5°C	2°C	2.5°C	3°C	3.5°C	4°C
Reticulated	2.0	1	5	6	7	7	8	8
		(0,7)	(2, 13)	(3, 14)	(3, 14)	(3, 15)	(4, 15)	(4, 16)
	1.5	12	13	13	14	14	15	15
		(6,19)	(7, 20)	(7, 20)	(7, 20)	(7, 22)	(7, 23)	(7, 24)
	-1.5	9	10	12	13	15	17	21
		(4,15)	(4, 19)	(4, 22)	(4, 28)	(5, 36)	(5, 41)	(6, 48)
	-2.0	0	3	4	6	8	9	11
		(0,6)	(0, 8)	(1, 10)	(1, 13)	(2, 18)	(2, 23)	(2, 29)
South African	2.0	1	0	0	0	0	0	0
		(0,11)	(0, 9)	(0, 7)	(0, 7)	(0, 7)	(0, 6)	(0, 6)
	1.5	12	6	4	3	2	1	1
		(4,21)	(0, 12)	(0, 11)	(0, 11)	(0, 11)	(0, 10)	(0, 10)
	-1.5	9	21	31	43	57	68	81
		(2,16)	(11, 69)	(12, 117)	(14, 137)	(16, 159)	(20, 197)	(23, 229)
	-2.0	1	11	16	24	34	46	59
		(0,10)	(3, 39)	(7, 97)	(8, 126)	(9, 148)	(11, 177)	(13, 213)
West African	2.0	2	4	5	7	6	7	7
		(0,7)	(3, 7)	(3, 9)	(3, 8)	(3, 9)	(4, 8)	(4, 9)
	1.5	11	9	10	10	10	10	9
		(7,12)	(6, 12)	(5, 12)	(5, 12)	(5, 12)	(6, 13)	(6, 14)
	-1.5	13	20	25	34	44	53	68
		(11,17)	(16, 29)	(22, 36)	(27, 49)	(34, 71)	(41, 76)	(55, 103)
	-2.0	4	10	14	19	24	29	44
		(0,11)	(4, 13)	(7, 18)	(10, 26)	(13, 42)	(19, 58)	(25, 65)

Land Cover

Between 1992 and 2022, landcover for each (sub)species was relatively consistent (Table 3.5). The largest land cover change as a percentage of a (sub)species range is a 4% reduction of shrubland within the Kordofan giraffe's range (from 41 to 37%), and a 4% reduction in two different types of tree cover in the Luangwa giraffe's range. In both 1992 and 2022, at least 26% of each (sub)species' range, except for West African giraffe, was comprised of shrubland. The (sub)species with the highest proportion of their range as agriculture is West African giraffe, which had 20% of their geographic range covered by agriculture in both 1992 and 2022. The only (sub)species that experienced a noticeable increase in agriculture cover between 1992 and 2022 are the Masai and Luangwa giraffe, which both had an increase of 1% of their geographic range. For Angolan and West African giraffe, grassland covers a large portion of their range at 36 and 41% in 2022, respectively. For all other species, grassland covers less than 15% of their geographic range in both years.

Table 3.5: Percentage land cover for each (sub)species' range in 1992 and 2022. Highlighted cells are those with values above 0%, with a continuous colour scale of yellow – dark green representing values 1-100%. Some columns may not total to 100% due to value rounding.

	Angolan		Kordofan		Luangwa		Masai		Nubian		Reticulated		South African		West African	
	1992	2022	1992	2022	1992	2022	1992	2022	1992	2022	1992	2022	1992	2022	1992	2022
Cropland, rainfed	1	1	2	2	4	5	9	10	5	5	2	2	4	4	20	20
Herbaceous cover	0	0	0	0	0	0	5	6	0	0	0	0	3	3	1	2
Tree or shrub cover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cropland, irrigated or post-flooding	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)	0	0	1	1	6	9	2	3	2	2	1	1	2	2	7	7
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)	0	0	1	1	1	2	2	1	1	1	2	2	2	2	7	7
Tree cover, broadleaved, evergreen, closed to open (>15%)	0	0	0	0	0	0	1	1	1	2	0	0	0	0	0	0
Tree cover, broadleaved, deciduous, closed to open (>15%)	0	1	0	2	17	13	14	13	0	2	0	0	6	5	0	0
Tree cover, broadleaved, deciduous, closed (>40%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tree cover, broadleaved, deciduous, open (15-40%)	2	2	45	46	41	37	19	19	5	6	2	2	10	10	0	0
Tree cover, needle leaved, evergreen, closed to open (>15%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tree cover, needle leaved, deciduous, closed to open (>15%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tree cover, mixed leaf type (broadleaved and needle leaved)	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	10	11	0	0	1	2	2	2	1	1	18	19	4	4	0	0
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	2	2	2	2	0	0	0	0	0	0	17	17	1	1	0	0
Shrubland	36	35	41	37	26	29	27	28	74	71	41	39	59	59	0	0
Deciduous shrubland	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Grassland	35	36	1	1	0	0	5	5	8	8	11	11	5	4	41	41
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	3	1	0	0	0	0	0	0	0	0	1	0	0	0	6	10
Sparse shrub (<15%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sparse herbaceous cover (<15%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	11
Tree cover, flooded, fresh or brackish water	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
Tree cover, flooded, saline water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shrub or herbaceous cover, flooded, fresh/saline/brackish water	0	0	3	3	0	0	5	5	2	2	3	3	2	2	0	0
Urban areas	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Bare areas	9	9	0	0	0	0	0	0	0	0	1	1	0	0	2	2
Consolidated bare areas	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Unconsolidated bare areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water bodies	2	2	1	1	1	1	3	2	0	0	0	0	0	0	0	0

Human population

Human population is projected to increase within the geographic range of all (sub)species up to 2100, except for South African giraffe where the population is projected to fall slightly after 2060 (Figure 3.4). The 2020 data shows that only Angolan, Kordofan and Luangwa giraffe have a total human population below one million within their current geographic range. From 2020 onwards, the geographic range of Masai giraffe contains the highest human population, with South African giraffe next highest. Kordofan and Masai giraffe are the only (sub)species where the human population extended to within a 15 km buffer is over double that of solely within the species' geographic range.

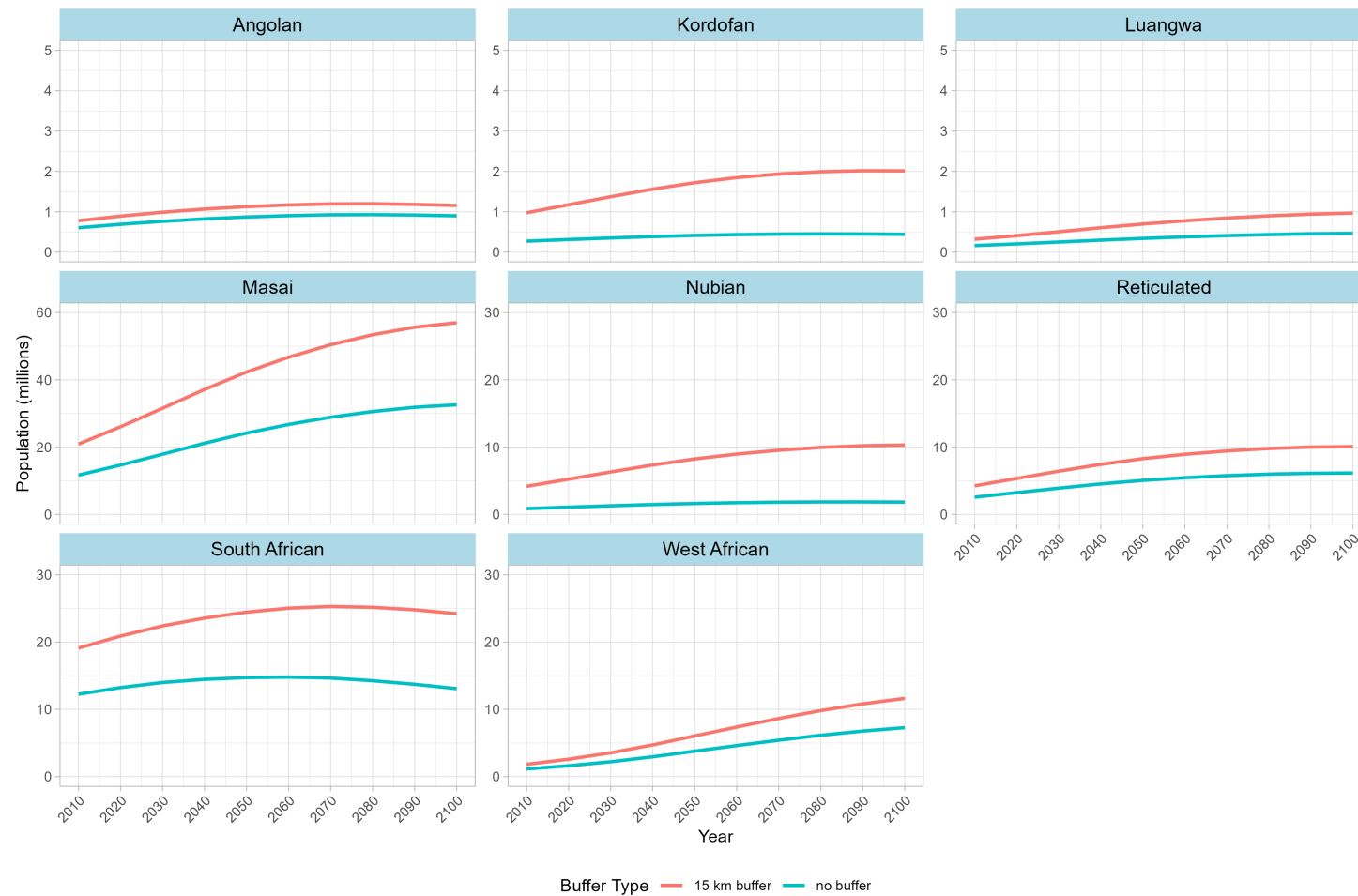


Figure 3.4: The summed count of human population within each (sub)species' geographic range from 2010 to 2100 using SSP2 projections (Gao, 2020). Blue lines show values inside the species' geographic range and red lines show values within their geographic range and an additional 15 km buffer.

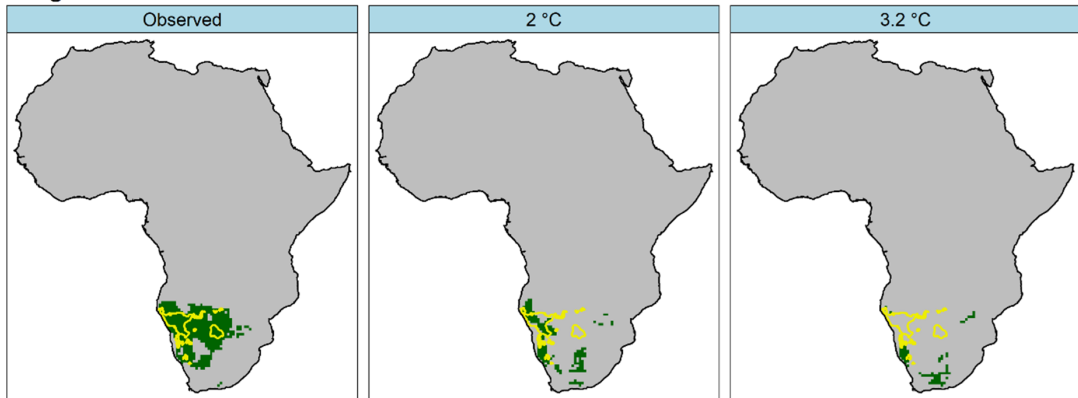
3.3.3 Novel Climate

The first metric of novel climate examined in this chapter is ‘novel climate for the (sub)species given the bounds of observed (1961-1990) temperature and precipitation values across their geographic range’. At a global warming level of 2°C, all species and subspecies except from Masai giraffe are projected to see novel climate conditions in over half of their current geographic range (Table 3.6; Figure 3.5). Masai giraffe are projected to experience novel climate conditions in only 15% of their range at this warming level. At 3.2°C of warming, many of the (sub)species are projected to experience novel climate in over 75% of their range. Masai giraffe are projected to experience novel climate in the lowest proportion of geographic range, at only 39% of their range. West African and Luangwa giraffe are both projected to experience novel climate conditions across 100% of their geographic range at 2 and 3.2°C global warming.

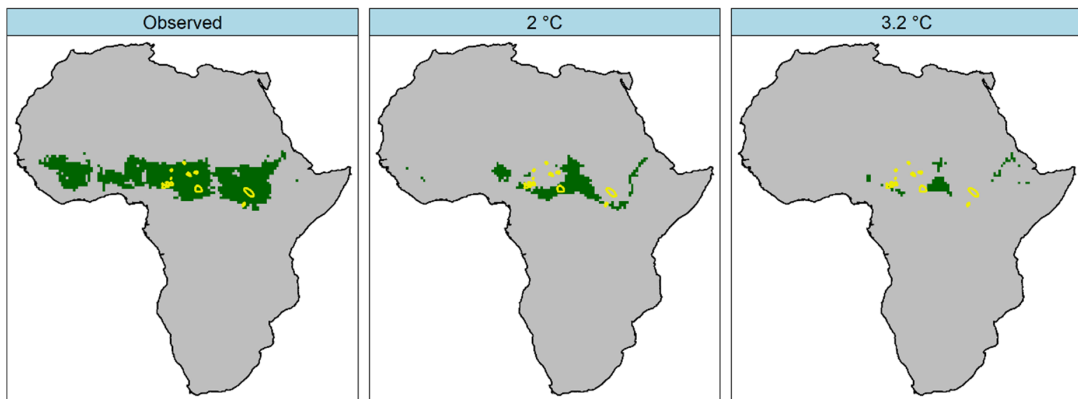
Table 3.6: Percentage of each (sub)species’ geographic range projected to be exposed to a novel climate at 2 and 3.2°C of global warming. For this analysis, novel climate was defined as one or more of the 12 input variables exceeding the observed values across the entire (sub)species’ geographic range.

(sub)species	Percentage of geographic range exposed to novel climate	
	(%)	
	2°C	3.2°C
Angolan	56	98
Kordofan	69	95
Luangwa	100	100
Masai	15	39
Nubian	84	98
Reticulated	52	82
South African	55	79
West African	100	100

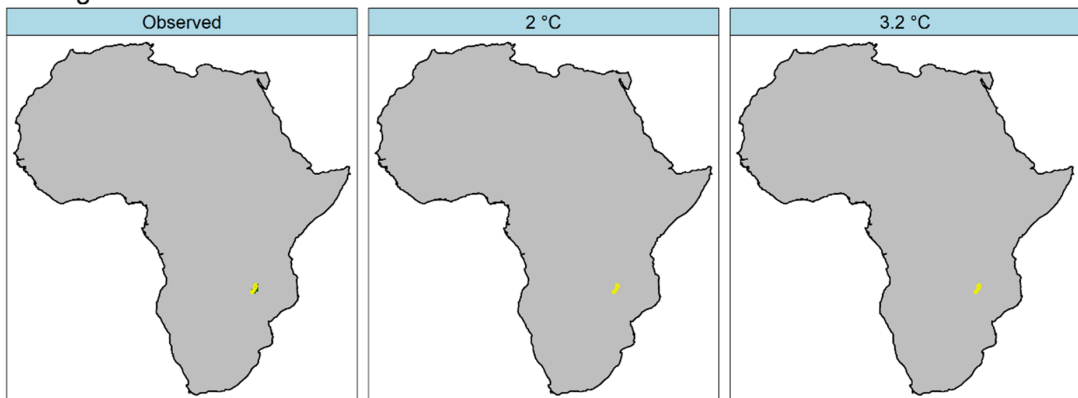
Angolan



Kordofan



Luangwa



Masai

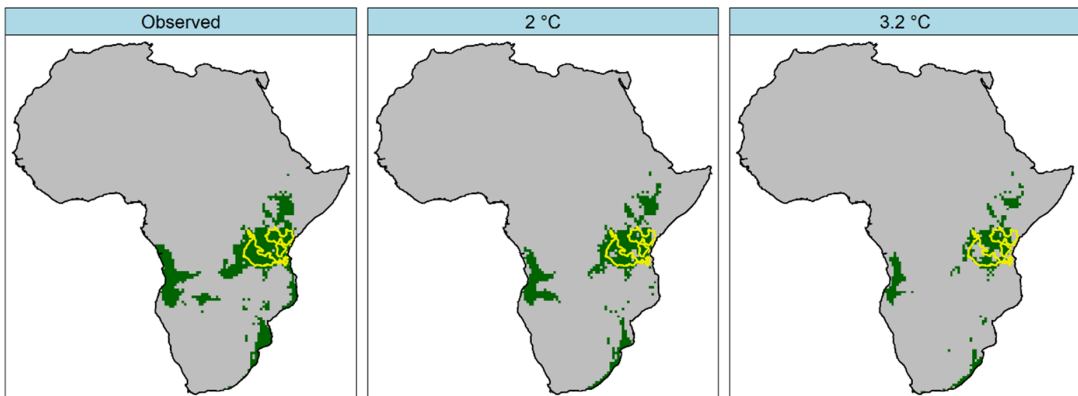
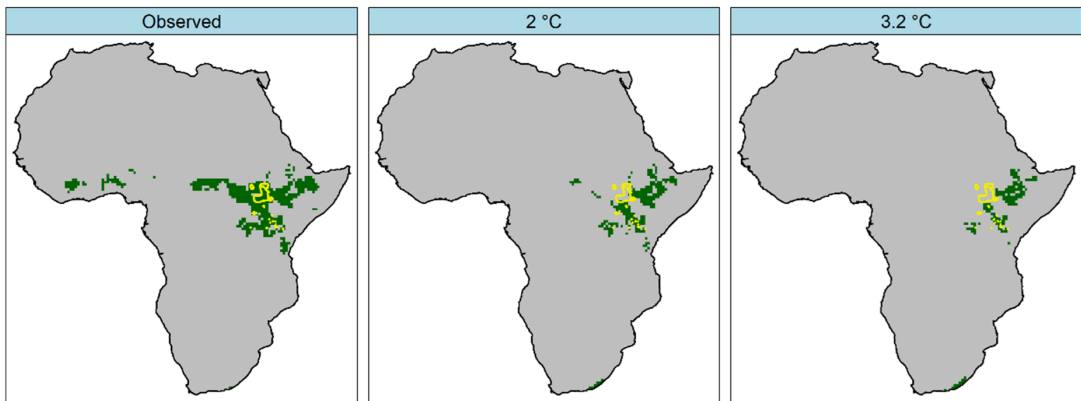
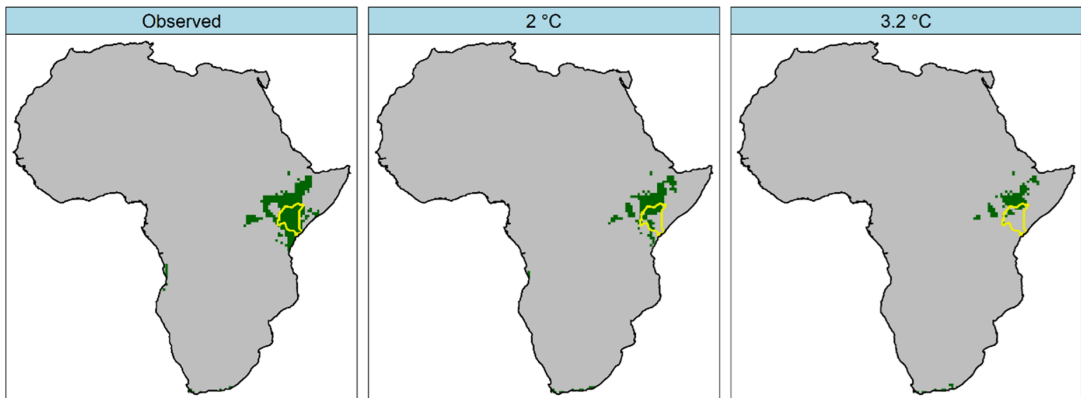


Figure 3.5: Areas which are within the upper and lower bounds of observed (1961-1990) seasonal temperature and precipitation values (green) across each (sub)species' geographic range (yellow outline), for 2 and 3.2°C global warming. Grey shows 'novel climate'.

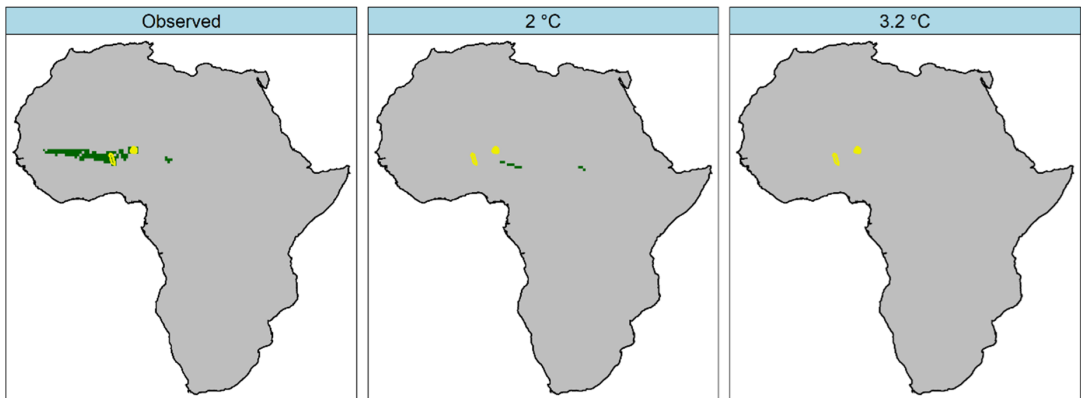
Nubian



Reticulated



West African



South African

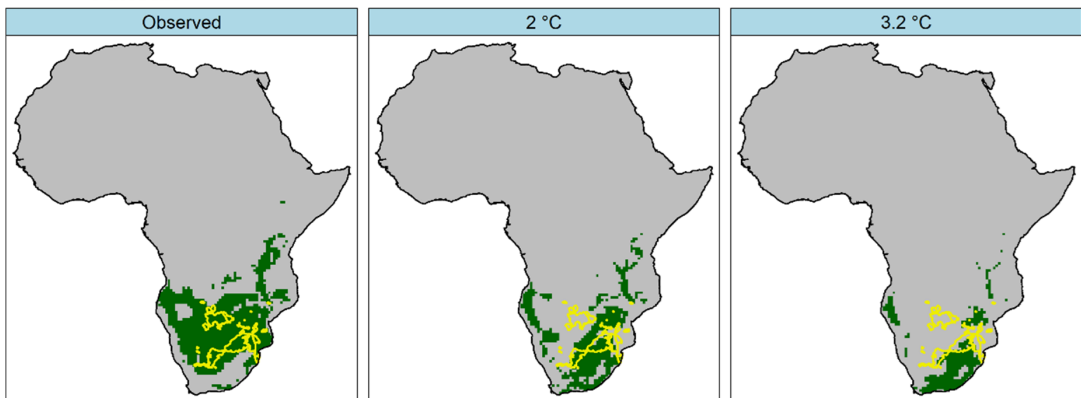


Figure 3.5: continued

For cell-specific novel climate, global warming levels of 2.7°C and higher are projected to cause 100% of all (sub)species' geographic ranges to experience novel temperature conditions (Table 3.7; Table 3.8). The only exception to this is the West African giraffe's geographic range which is projected to have 51% of the range exposed to novel values of maximum temperature at 2.7°C. More (sub)species are projected to be exposed to novel climate across 100% of their range at 1.5°C global warming for seasonal minimum temperature (Table 3.8) compared to seasonal maximum temperature (Table 3.7).

Table 3.7: The percentage of each (sub)species' geographic range exceeding 2 standard deviations of observed average seasonal maximum temperature, at each warming level and season. Highlighted cells show those with a value of less than 100%.

Species/ subspecies	Season	1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Angolan	DJF	76	81	100	100	100
	MAM	77	82	100	100	100
	JJA	100	100	100	100	100
	SON	100	100	100	100	100
Kordofan	DJF	47	61	100	100	100
	MAM	91	100	100	100	100
	JJA	80	100	100	100	100
	SON	71	100	100	100	100
Luangwa	DJF	100	100	100	100	100
	MAM	0	100	100	100	100
	JJA	100	100	100	100	100
	SON	100	100	100	100	100
Masai	DJF	53	73	100	100	100
	MAM	62	93	100	100	100
	JJA	100	100	100	100	100
	SON	83	100	100	100	100
Nubian	DJF	0	14	100	100	100
	MAM	3	79	100	100	100
	JJA	15	96	100	100	100
	SON	1	15	100	100	100
Reticulated	DJF	0	8	100	100	100
	MAM	2	78	100	100	100
	JJA	97	100	100	100	100
	SON	1	82	100	100	100
South African	DJF	1	17	100	100	100
	MAM	1	34	100	100	100
	JJA	70	99	100	100	100
	SON	95	100	100	100	100
West African	DJF	0	0	51	100	100
	MAM	98	100	100	100	100
	JJA	49	100	100	100	100
	SON	96	100	100	100	100

Table 3.8: The percentage of each (sub)species' geographic range exceeding 2 standard deviations of observed average seasonal minimum temperature, at each warming level and season. Highlighted cells show those with a value of less than 100%.

Species/ subspecies	Season	1.5°C	2.0°C	2.7°C	3.2°C	4.5°C
Angolan	DJF	100	100	100	100	100
	MAM	100	100	100	100	100
	JJA	94	100	100	100	100
	SON	92	100	100	100	100
Kordofan	DJF	96	100	100	100	100
	MAM	93	100	100	100	100
	JJA	100	100	100	100	100
	SON	100	100	100	100	100
Luangwa	DJF	100	100	100	100	100
	MAM	100	100	100	100	100
	JJA	100	100	100	100	100
	SON	100	100	100	100	100
Masai	DJF	89	100	100	100	100
	MAM	100	100	100	100	100
	JJA	98	100	100	100	100
	SON	91	100	100	100	100
Nubian	DJF	44	99	100	100	100
	MAM	83	100	100	100	100
	JJA	90	100	100	100	100
	SON	99	100	100	100	100
Reticulated	DJF	99	100	100	100	100
	MAM	100	100	100	100	100
	JJA	99	100	100	100	100
	SON	100	100	100	100	100
South African	DJF	98	100	100	100	100
	MAM	85	100	100	100	100
	JJA	53	97	100	100	100
	SON	90	98	100	100	100
West African	DJF	0	100	100	100	100
	MAM	0	100	100	100	100
	JJA	95	100	100	100	100
	SON	100	100	100	100	100

3.4 Discussion

This research has highlighted the differences in observed climate and climate change exposure within the current geographic ranges of different species and subspecies of giraffe. The cluster analyses for the observed (1961-1990) climate period identified groupings of similar and dissimilar climates between species and subspecies. The cluster analysis at 3.2°C of warming further showed that separate (sub)species' geographic ranges may become more climatically distinct under high levels of global warming. All

(sub)species are projected to be exposed to rising temperatures and changes to observed precipitation patterns. In addition to this, maximum consecutive months of severe drought are projected to increase under higher warming levels for all species. Given these trends, it is unsurprising that most species are projected to experience novel climate conditions (those outside of the bounds experienced within their current geographic range, but potentially not outside of the historical climate bounds) across a majority of their range by 2°C of warming. These findings highlight the importance of understanding climate change exposure within individual (sub)species' ranges to guide targeted conservation actions, particularly in areas where species' movement may be impacted by physical barriers or fragmented landscapes. The additional consideration of human population growth and historical land cover change demonstrates how species might be exposed to compounding stressors on top of climate changes, especially if observed trends of land cover change continue.

The finding that giraffe (sub)species inhabit climatically distinct regions suggests that there may be species-specific adaptations to climate. Genetic studies of the speciation in giraffe suggest that Pleistocene climate oscillations and the associated shifts in rainfall patterns and vegetation may have been caused repeated episodes of isolation between populations (Bertola *et al.*, 2024). Similarly, it has been found that the timing of rainfall maintains the separation of giraffe (sub)species populations in Kenya through subsequent vegetation patterns (Thomassen *et al.*, 2013). Whilst climate-driven speciation does not inherently confer differences in climate adaptation, it is not uncommon for isolated populations to undergo local adaptation to their specific environmental conditions over long periods of time. It is therefore possible that the current distribution of giraffe across areas of distinct climate may reflect local adaptation to differing climatic conditions. One observation which potentially lends support to this theory is the distinct pelage patterns found on different species and subspecies of giraffe (Dagg, 1962). Researchers have long suggested that the patches (darker spots) on giraffe coats may play a role in thermoregulation and heat loss due to the associated vascular structures underlying these patches (Mitchell and Skinner, 2004). Recent research even found a link between Masai giraffe survival and patch shape and size, during periods of high and low temperature anomalies (Mouchet *et al.*, 2025). It is possible therefore, that pelage may play a role in the local adaptation of giraffe species to temperature extremes.

Both maximum and minimum temperature are projected to increase across all giraffe (sub)species' ranges. Whilst (sub)species have differing exposure to this, all ranges are projected to see an increase in maximum temperature of at least 1.3°C at 2°C warming, and 2.4°C at 3.2°C warming. Angolan and South African giraffe, both subspecies of Southern giraffe, are the subspecies projected to be exposed to the largest changes in maximum temperature. Similarly, minimum temperature is projected to increase by 1.5°C and 2.6°C at 2 and 3.2°C of global warming, respectively. Giraffe are well adapted to survive in hot, arid environments: their dolichomorphic body shape aids heat loss and behavioural adaptations for keeping cool include orientating to face the sun and seeking shade (Mitchell *et al.*, 2017). High seasonal temperature anomalies have even been shown to correlate with increased adult survival rates in a population of Masai giraffe in the Tarangire Ecosystem in Tanzania (Bond *et al.*, 2023). However, increases in minimum daily temperature might increase heat stress if giraffe are unable to cool off overnight. In addition to this, giraffe movement can be impacted by seasonal temperature, with giraffe moving more in cooler seasons (Deacon *et al.*, 2023). Irrespective of this, all species have a thermal tolerance threshold above which mortality increases. Although the specific threshold for giraffe remains unclear, it is generally thought that species are unable to survive outside of climatic spaces that they already inhabit (IPCC, 2023). Given this, the results showing the high percentages of species' geographic ranges where the average projected temperature exceeds 2 standard deviations of the observed temperature are particularly informative. A measure of 2 standard deviations is the equivalent of a one in 20-year climate event, and so projections of these rare events becoming the species' new climatic norm under warming scenarios is concerning.

Projections of rainfall show more variability between species and seasons than projections for temperature. Rainfall is particularly important for giraffe – higher rainfall is heavily correlated with reduced home range sizes, likely due to the subsequent impact on primary productivity and available forage (Knüsel *et al.*, 2019). Differences in the timing of seasonal rainfall and the associated forage availability is also thought to aid in maintaining divergence between genetically distinct, yet geographically close species of giraffe (Thomassen *et al.*, 2013). Angolan and South African giraffe are projected to see consistent drying trends across all seasons at increasing levels of global warming, whilst Reticulated giraffe are projected to experience increasing precipitation in all seasons except for

June-August. For the remaining species/subspecies, projections of drying and wetting depend on the season.

These rainfall and temperature trends are similarly reflected in the projections of extreme wet and dry conditions. The maximum consecutive months of severe drought increases across all species, with implications for food and water availability. Angolan, South African, and West African giraffe are most exposed to changes, with projections of 25 to 37 months of consecutive drought in a 30-year period, as a median across their geographic ranges at 2°C warming. There have been many observations of giraffe death due to drought conditions (Alasaad *et al.*, 2012; International Fund for Animal Welfare (IFAW), 2023), and juveniles and large adult males can be particularly susceptible (Mitchell *et al.*, 2010). Moreover, competition for remaining water sources between wildlife, local people, and livestock may exacerbate these challenges.

Non-climatic, anthropogenic threats have been a main cause of population decline across most giraffe populations, in particular habitat loss, degradation and fragmentation, and poaching (Muller *et al.*, 2018). At the spatial extent used in this chapter, increases in cropland between 1992 and 2022 were only observed in Masai and Luangwa geographic ranges, and increases in urban areas were only found in the South African giraffe's geographic range. This increase in agriculture, particularly in the Masai giraffe range in northern Tanzania has been documented by others across similar time periods (Msoffe *et al.*, 2011). The projected increases of human population across each (sub)species' geographic range highlight the potential for further urban expansion and conversion of suitable habitat to agricultural land. Studies on future land use changes have used historical land use trends alongside projections of human population to project land use and land cover (Sleeter *et al.*, 2017). Additionally, there is the potential for increased poaching with increasing human population. Higher human population may result in increased demand for bushmeat, and the expansion of settlements may lead to greater spatial overlap between people and wildlife – increasing opportunities for illegal hunting (Knapp *et al.*, 2010). However, poaching rates are affected by multiple factors, including local poverty and national corruption (Hauenstein *et al.*, 2019). These observed and projected trends highlight the need to consider anthropogenic impacts alongside projections of climate change when planning conservation actions.

The novel climate analysis provides a useful insight into the exposure of giraffe to climate change, but it is important to note that it is highly influenced by the species' current geographic range extent. Where species have faced range reductions driven by non-climatic factors, their current climate bounds may not represent their full climatic niche. For example, the West African giraffe has undergone a significant population decline in recent decades (Ciofolo, 1995), and its projected exposure to novel climates is likely at least partly due to the limited range extent, which reduces the breadth of climates it currently encounters. As such, the analysis in this chapter and characterisation of novel climates is based upon the species' realised niche, rather than the potentially wider fundamental niche (Hutchinson, 1957). This is a common issue in climatic niche analyses where species have faced substantial range contractions driven by non-climatic factors (Elith and Leathwick, 2009; Townsend *et al.*, 2012). This approach nonetheless offers a useful indication of areas outside the bounds of climate experienced across the entire species range. However, it does not specify the extent to which the climate bound is exceeded, nor by which variable. This analysis can be informative in identifying areas which may remain suitable for giraffe under climate change and can be used as an alternate metric of assessing future climate suitability alongside species distribution models.

Where giraffe are unable to disperse, information on climate change exposure is particularly useful. Given that 30% of giraffe range area is within Government-Managed Protected Areas, understanding the projected climate changes within each range area is important for planning climate change informed adaptive conservation actions. In areas where rainfall is projected to decrease compared to observed levels, the water availability for giraffe (either through succulent browse or surface water) may be insufficient. In these cases, artificial watering holes could be an effective strategy to minimise the impact of reduced drinking water (Epaphras *et al.*, 2008). Furthermore, given the projected increases in human population, and thus increases in associated risks such as poaching and urban expansion, protected areas will likely remain a key conservation tool in the future. Understanding the climate changes within these areas provides protected area managers with the knowledge needed to pre-empt potential climate changes and suitable adaptation measures. Where climate change exposure is particularly bad, translocations to other protected areas may be deemed a necessary action.

These findings on the variability of climate change exposure between species and subspecies has highlighted the importance of well-informed, species-specific climate change adaptation measures. Broad, uniform conservation strategies may fail to address the specific vulnerabilities of each species or subspecies, and given the limited resources in the conservation sector, it is important to make well-informed actions. Targeted actions, such as habitat restoration, translocations to climatically suitable areas, or the establishment of corridors to facilitate range shifts, can enhance the resilience of giraffe populations to climate change. Where translocations into other giraffe range areas may be appropriate, the results of the cluster analysis, highlighting the most climatically similar ranges may aid in decision making. Ultimately, species-specific measures not only increase the likelihood of effective conservation outcomes but also ensure that limited resources are used in the most impactful way for each species' and subspecies' individual context.

There are several limitations to this research that should be acknowledged. Firstly, the use of species range maps involves some inherent uncertainties. Range maps can often be outdated or imprecise, and they fail to account for finer-grain species occurrence within these areas. The range maps used in this chapter are from a well-evidenced and recently updated source (see O'Connor *et al.*, 2019), and so it is unlikely that the quality of the range maps is a substantial issue for this research. Additionally, given the coarse resolution of climate data used in this research, fine-scale habitat suitability within these range areas is less of a concern and would not be captured in the climate data regardless. Secondly, this coarse use of climate data may overestimate the exposure of species to climate change by failing to account for local variability and microclimate refugia. Given this, these research outputs should be considered in tandem with local knowledge and fine-scale data. Thirdly, by examining the projected changes in climate without establishing causal links between climate and giraffe, there is a level of uncertainty surrounding how giraffe may respond to these changes in climate.

This chapter is designed to give a broad context of the exposure of giraffe within their current range areas to climate change, and to accompany it, the next chapter will focus on building species distribution models to better project changes in climate suitability for each giraffe species. Whilst projected changes in human population growth and previous patterns of land cover change were examined, there will be many additional impacts at

these warming levels and associated time periods that are not accounted for (such as impacts on predators and food sources). These impacts will be explored further in Chapter 5: 'Beyond mean climate: A comprehensive approach to prioritising areas for giraffe conservation under climate change'.

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Identifying areas of climate change refugia as a least-regrets conservation strategy for giraffe species

Abstract

Given the uncertainties surrounding future realised global warming levels, identifying species-specific areas of climate refugia offers a 'least-regrets' approach to conservation planning. This is particularly important for species which have experienced human-induced geographic range declines. The recent update of giraffe taxonomy to four distinct species rather than one, necessitates an update to previous projections of climate suitability under global warming. In this chapter, four species distribution models (SDMs) were developed for each of the four giraffe species, using occurrence data from GBIF combined with GPS tracking data from the Giraffe Conservation Foundation (GCF). These SDMs were projected under four global warming scenarios of 1.5°C, 2°C, 2.7°C, and 3.6°C, using 22 CMIP6 GCMs. All SDMs performed well: Area Under the Receiver Operating Curve (ROC) values were all above 0.9, and all True Skill Statistic (TSS) values were above 0.7. Results showed that all four species are projected to lose suitable climate area as global warming increases. However, even under the highest warming level of 3.6°C, all species retain areas of suitable climate. Climate refugia for each giraffe species covered at least 24% of their current geographic range, with Reticulated giraffe having the smallest proportion of their geographic range as climate refugia, and Northern giraffe having the largest

proportion. Importantly, over 50% of climate refugia for Northern, Masai, and Reticulated giraffe are within existing protected areas, emphasising the importance of these areas for giraffe conservation. This research has highlighted the importance of species-specific climate suitability projections under future global warming scenarios and has contributed to a 'least-regrets' conservation approach by identifying areas of climate refugia.

4.1 Introduction

Climate change is affecting the distribution of species as they move to track areas of suitable climate (Parmesan, 2006). Typically, terrestrial species' ranges are expected to shift poleward or to higher altitudes, and many taxa have already shown substantial range changes following this pattern (Parmesan and Yohe, 2003; Root *et al.*, 2003). In species with limited dispersal ability or where dispersal is constrained by factors such as fragmented landscapes, ranges may instead decline rather than shift (Corlett and Westcott, 2013; Opdam and Wascher, 2004; Schloss *et al.*, 2012). Similarly, microclimate refugia and phenotypic plasticity may allow species to persist in their current ranges without the need for dispersal (Ashcroft, 2010; Charmantier *et al.*, 2008). The expected degree of range shifts or declines also depends heavily on the level of global warming reached. Projections have shown that a warming of 2°C could double the number of plants and vertebrates losing more than 50% of their range, compared to 1.5°C (Warren *et al.*, 2018). This uncertainty surrounding species' responses to a changing climate, alongside uncertainties in climate projections themselves, makes it difficult to incorporate climate change planning into present-day conservation actions.

Giraffe (*Giraffa spp.*) are considered highly charismatic species (Albert *et al.*, 2018) that play a large role in shaping their environments (Fleming *et al.*, 2006; Hyvarinen *et al.*, 2021; Keesing, 2000). Recent genetic and genomic analyses classify giraffe into four species with seven subspecies: Masai (*Giraffa tippelskirchi*), Reticulated (*Giraffa reticulata*), Southern (*Giraffa giraffa*), and Northern (*Giraffa camelopardalis*) (Coimbra *et al.*, 2021; Fennessy *et al.*, 2016; Winter *et al.*, 2018). These species can be found in 21 different countries across Sub-Saharan Africa (O'Connor *et al.*, 2019), usually in highly fragmented populations (Shorrocks, 2016). Listed as one species in the IUCN, they are categorised as 'Vulnerable' due to population declines of ~40% over the last few decades (Muller *et al.*, 2018). The

latest research shows that the four species have populations of between ~6000 to ~50,000 individuals (Brown *et al.*, 2021). Furthermore, subspecies classifications (which incorporate the four species above) on the IUCN red list vary from 'Least Concern' to 'Critically Endangered' (Fennessy and Marais, 2018; Marais *et al.*, 2020).

Each population of giraffe is exposed to a variety of threats, but regardless of the species, the most prominent threats are habitat loss, poaching, and climate change (Muller *et al.*, 2018; Shorrocks, 2016). Many of the conservation actions employed to tackle these threats are spatially explicit. For example, giraffe can be translocated into historical range areas and Protected Areas (PAs) to bolster current populations or establish new ones (O'Connor *et al.*, 2019). Whilst recent conservation efforts have resulted in population increases (Brown *et al.*, 2021; Muller *et al.*, 2018), the long-term effectiveness of these spatially explicit actions could be hampered by a changing climate. Across Sub-Saharan Africa, climate change is projected to cause increasing temperatures (Ranasinghe *et al.*, 2021), along with longer periods of drought in southern and western Africa (Ukkola *et al.*, 2020). Rainfall projections vary across and within regions, with many parts of southern Africa projected to see a decrease in rainfall and areas in eastern Africa projected to see an increase (Hoegh-Guldberg *et al.*, 2018; Lee *et al.*, 2021). Not only could this shift and/or reduce suitable range areas for giraffe, but there are also several documented cases of giraffe mortality following periods of drought (Ciofolo, 1995; Mitchell *et al.*, 2010; Okello *et al.*, 2015), and evidence of high temperatures constraining giraffe movement (Hart *et al.*, 2020).

Species distribution models (SDMs) are commonly used to project the distribution of species under current and future climate scenarios. The three main types of SDM are statistical, traits-based, and mechanistic (Pacifi *et al.*, 2015). Statistical SDMs build statistical relationships between climate variables and species occurrence data, which can then be applied to future climate scenarios (Elith and Leathwick, 2009). The disadvantage of these models is that they assume an equilibrium between the species and its environment, and they do not inherently factor in demographic processes, biotic interactions, or species' dispersal ability (Zurrell *et al.*, 2009). Traits-based SDMs incorporate the link between species' functional traits, for example, leaf area or seed mass in plants (Pollock *et al.*, 2018) and environmental variables, using traits as a direct predictor variable in statistical models. Traits-based models have been shown to have similar

predictive performance to statistical SDMs, but can be particularly useful when the research aim is to understand why environmental responses might vary between species (Brown *et al.*, 2014). However, they can be more limited owing to the lack of relevant traits-based data for many species. Mechanistic models are the most data-intensive of the three methods, incorporating data on species' physiological limits and responses to build a process-based link between environmental variables and the fundamental niche of a species (Kearney and Porter, 2009). Most mechanistic SDMs have been performed for data-rich species, particularly plants and ectotherms (Huey *et al.*, 2012). Despite a growing understanding of giraffe physiology (Mitchell, 2021), knowledge gaps on thermal tolerance limits, water dependency, and the potential of species-specific differences in physiology make this an unsuitable choice for modelling the distribution of giraffe. Statistical SDMs were therefore deemed the most appropriate choice for understanding the potential impact of climate change on the distribution of giraffe.

Martínez-Freiría *et al.* (2016) previously modelled the potential effects of climate change on giraffe to assess how the inclusion of historical occurrence data can influence model accuracy in species with human-induced range reductions. Whilst informative, the new four-species taxonomy calls for an update to previous models. The species occupy geographically distinct areas, and the hierarchical cluster analysis from Chapter 3 suggests they may have different climatic niches. Updated species-specific models are needed to provide critical information to conservationists on the future climatic suitability of giraffe habitats.

This chapter builds on previous research by examining several novel aspects of how climate change may impact giraffe. Firstly, each of the four species is modelled separately to reflect the revised taxonomy and capture any differences in species-level responses to climate change. Secondly, areas of climate refugia – those which are climatically suitable for the species now and which maintain climatic suitability across all warming levels – are identified to inform a least-regrets conservation strategy. Given the uncertainty surrounding climate projections and realised global warming levels, this approach minimises the risk of wasting conservation resources on actions which may not have the desired effect under higher warming levels. The aim of this chapter is therefore to determine how suitable range area for each giraffe species might be affected by climate

change. Specifically, it aims to answer the following research question: ‘*For each of the four giraffe species, how is suitable climate projected to change, and are there any areas of climate refugia?*’.

To answer this question, four species distribution models (GLM, GBM, GAM, Maxent) were developed for each giraffe species and projected across observed climate (1970-2000) and four global warming scenarios, using 22 CMIP6 General Circulation Models (GCMs). This methodology accounts for uncertainties caused by differences in SDM algorithms, pseudo-absence generation, GCMs, and environmental variable selection. These results can be used to inform ‘least-regrets’ conservation strategies, where areas of internal climate refugia are highlighted as conservation priorities in the face of uncertainties surrounding future climate conditions. This approach minimises the risk of investing limited conservation resources into actions that may prove ineffective if realised climatic conditions differ from projections.

4.2 Methods

4.2.1 Study extent

The mainland continent of Africa was used as the study extent for each species’ SDM. This extent was chosen to generate the pseudo-absence points across a range of available climates; smaller study extents were initially explored, but did not include sufficient coverage to capture relevant pseudo-absence data (see below section 4.2.3 for more detail on pseudo-absences). The *rnaturalearth* (South, 2017) and *terra* (Hijmans, 2022) R packages were used to create a polygon of mainland Africa at a scale of 1:50, which all predictor variables were cropped to. All SDM outputs were then clipped to a final study extent using a buffer of 300 km around the species’ current range area, to allow for potential realistic dispersal (Figure 4.1).

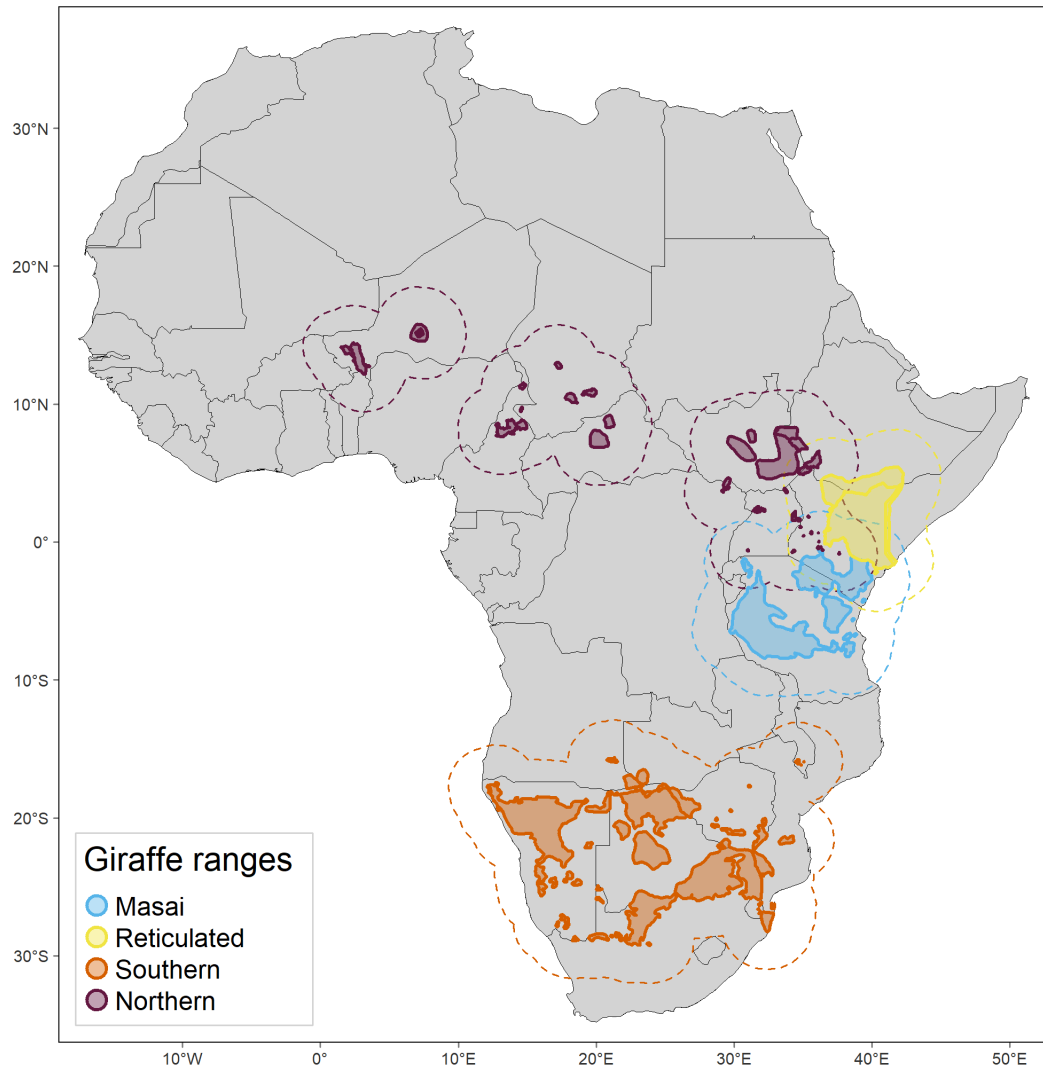


Figure 4.1: The study extent used to generate pseudo-absence data (grey) and the geographic range of each giraffe species. Dotted lines show the 300 km buffer that each SDM output was clipped to.

4.2.2 Occurrence data

Giraffe occurrence data was compiled from multiple sources: the Giraffe Conservation Foundation (GCF), Martínez-Freiría *et al.* (2016), Global Biodiversity Information Facility (GBIF; GBIF.org, 2023), and the IUCN red list assessment (Ogutu *et al.*, 2018, supplementary material). GCF provided data of GPS locations of tagged giraffe and aerial surveys, and data supplied by Martínez-Freiría *et al.* (2016) was that used in their own research, gathered through a literature review (see their supplementary materials for a list of sources). Data from the IUCN red list was georeferenced in ArcGIS Pro 3.0.2 (Esri, 2022) from an image of giraffe occurrence points obtained from surveys. GBIF data was

downloaded using the filters 'Occurrence status: present' and 'Scientific name: *Giraffa* Brisson, 1762'. This data was then cleaned in R 4.2.1 (R Core Team, 2022) using the *CoordinateCleaner* package (Zizka *et al.*, 2019), Microsoft Excel (Microsoft Corporation, 2022), and ArcGIS Pro 3.0.2 (Esri, 2022). Cleaning steps included removing records without coordinates, records outside of mainland Africa or those in the sea, fossil or specimen records, and records with identical longitude and latitude values. All removed records were examined further in ArcGIS Pro and MS Excel and added back to the dataset if they could be cleaned and were deemed reliable. All records were checked for correct species assignment, and some records were altered using up-to-date species range maps to reflect the new species designation. Any records where species labels could not be confidently assigned were removed.

Occurrence records were kept if they were dated between the start of the 30-year observed climate period and the present day. Whilst it is generally considered good practice to only use occurrence records matching the dates of the input climate data, more recent records were included for several reasons. Firstly, occurrence datasets for each species had the most complete range coverage when including the more recent data points. Secondly, due to habitat loss, giraffe range area has constricted rather than shifted over recent decades, and the recent occurrence records likely reflect presences from the observed climate time period. This may not be true in all instances, and it is acknowledged as a source of uncertainty in the data. Similarly, previous research has shown that, for species which have undergone considerable human-induced range reductions, excluding historical occurrence data can lead to an underestimation of the species' climatic niche (see Martínez-Freiría *et al.*, 2016). However, due to uncertainties surrounding the assignment of the revised four-species taxonomy to historical records, this data was not included in the primary analysis presented in this chapter. Instead, a sensitivity analysis examining the influence of including the historical occurrence records is presented in the Supplementary Material.

For each species, the cleaned records from each source were combined into one dataset and then spatially thinned to one record per 20 km to align with the spatial resolution of the predictor variables and reduce spatial bias. The dataset for Southern giraffe was thinned to 100 km after initial model runs showed increased spatial bias affecting model outputs.

All records were thinned in R, following the method from Strimas-Mackey *et al.* (2023) and using the R package *dggridR* (Barnes and Sahr, 2023).

Occurrence datasets for each giraffe species included records for all the subspecies, except for Masai giraffe where the Luangwa giraffe subspecies (*Giraffa tippelskirchi thornicrofti*), was not modelled. Preliminary models including this subspecies were not able to capture both subspecies' current geographic ranges without substantial commission errors. As such, all occurrence points for this subspecies were removed from Masai giraffe models.

The final occurrence datasets consisted of 462 records for Masai giraffe, 165 for Northern giraffe, 102 for Reticulated giraffe, and 130 records for Southern giraffe (see the Supplementary Material for a map of occurrence records).

4.2.3 Pseudo-absence data

A majority of SDMs require data on both species' presence and absence, but absence data can be difficult to obtain; for a highly mobile species with a large range size, such as giraffe, high-intensity sampling would be needed (Mackenzie and Royle, 2005). Where true absence data is unavailable, pseudo-absences can be generated by sampling points in the landscape (Barbet-Massin *et al.*, 2012). For each species, five pseudo-absence datasets of 10,000 points were generated across the study extent and used for all model runs. Using the same pseudo-absences for each model run reduces potential uncertainties in model outputs caused by pseudo-absence data generation. Each pseudo-absence dataset was generated randomly in R using the *biomod2* package (Thuiller *et al.*, 2023) and the 'disk' method. This method generates points within a minimum and maximum distance from occurrence points. The minimum distance was set at 20 km to account for potential giraffe home range size (up to ~200 km²; Knüsel *et al.*, 2019), as well as grid cell resolution of the predictor variables (~20 km). The maximum distance was set at 9,000 km to capture the entire study area of mainland Africa. Whilst VanDerWal *et al.* (2009) suggest that pseudo-absences should be generated from within 200 km of occurrences, initial model runs showed that this approach, and increases to 2000 km, did not capture a wide enough range of climates and led to high levels of commission errors in model outputs.

4.2.4 Predictor variables

Observed and projected climate variables were downloaded from WorldClim 2.1 at 10 minute resolution (~20 km at the equator) (Fick and Hijmans, 2017). This data consists of 19 bioclimatic variables derived from temperature and precipitation. Observed data is an average over the 30-year period 1970-2000, generated from weather stations and interpolated using thin-plate splines and satellite data (Fick and Hijmans, 2017). Future projected bioclimatic variables, which are downscaled and bias-corrected using the WorldClim 2.1 baseline (1970-2000) data, were downloaded for each of 22 CMIP6 GCMs under four SSPx-y combinations (see Chapter 2 section 2.1.5 ‘Climate change projections’ for more information on the SSPx-y scenarios). These projected climate scenarios represent a global surface air temperature change of 1.5, 2.0, 2.7, and 3.6°C relative to 1850-1900 (Table 4.1). Each model was run using five bioclimatic variables to avoid overfitting (see section 4.2.5 ‘Species distribution models’ for more information on variable selection).

Table 4.1: 20-year averaged global surface air temperature (GSAT) change for each SSPx-y and timeframe, relative to 1850–1900. Values show the central estimate, and 5-95% range in parentheses. Highlighted cells show the SSP-RCP scenarios and timeframes used in this thesis, and the equivalent GSAT. Adapted from Table 4.5 in Lee *et al.* (2021, p. 582).

Time Period	SSP1-1.9 (°C)	SSP1-2.6 (°C)	SSP2-4.5 (°C)	SSP3-7.0 (°C)	SSP5-8.5 (°C)
2021–2040	1.5 (1.2, 1.7)	1.5 (1.2, 1.8)	1.5 (1.2, 1.8)	1.5 (1.2, 1.8)	1.6 (1.3, 1.9)
2041–2060	1.6 (1.2, 2.0)	1.7 (1.3, 2.2)	2.0 (1.6, 2.5)	2.1 (1.7, 2.6)	2.4 (1.9, 3.0)
2081–2100	1.4 (1.0, 1.8)	1.8 (1.3, 2.4)	2.7 (2.1, 3.5)	3.6 (2.8, 4.6)	4.4 (3.3, 5.7)

4.2.5 Species distribution models

SDM models were run using the R packages ‘Biomod2’ and ‘ENMeval’, and the workflow was identical for each of the four giraffe species. To account for uncertainties between SDM methods, four different algorithms were used: General Additive Model (GAM), Generalised Linear Model (GLM), Maxent (Maximum Entropy), and Generalised Boosting Models (GBM; also called Boosted Regression Trees). These models were chosen because they have been shown to have good transferability and prediction accuracy (Heikkinen *et al.*, 2012). It is important to note that the purpose of using multiple model algorithms is not to compare

model performance, but to explore any differences in the projections of climate suitability and uncertainty. The following workflow describes the process for each algorithm-species combination.

To select the five predictor variables that would be used in each of the final models, all 19 bioclimatic variables were used in a preliminary model and their variable importance scores were extracted and assessed. This preliminary model was run using default model parameters, five variations of 5-fold cross validation, five variable importance permutations, and all 19 bioclimatic variables. Due to computing and time constraints, GAM models were run with only one 5-fold cross validation split. For each model, the variable importance scores from *biomod2* were averaged across all runs (five pseudo-absence datasets, five variations of 5-fold cross validation) to attain a final score for each variable. For Maxent models, variable importance was assessed using averaged permutation importance outputs. One issue with selecting input variables using this method is correlation between variables; whilst multicollinearity does not directly affect model prediction, it can inflate variable importance scores. Additionally, where variables are somewhat correlated, removing one can lead to the omission of a biologically relevant variable. To address this, VIF scores were generated, and where variable importance scores had likely been inflated, the variables were swapped for the next highest-ranking variable. Similarly, it was ensured that the final variable selection included both temperature and precipitation derived variables; if this was not the case, the lowest scoring variables were swapped out. Table 4.2 shows the final variable selection for each species and algorithm.

Table 4.2: The bioclimatic variables from WorldClim 2.1 that were used for each species and SDM algorithm. Bioclimatic variables are calculated using average monthly values over the time period (i.e. 1970–2000 for the observed climate period)

Bioclimatic Variable	Northern				Reticulated				Southern				Masai			
	GAM	GBM	GLM	Maxent	GAM	GBM	GLM	Maxent	GAM	GBM	GLM	Maxent	GAM	GBM	GLM	Maxent
Annual Mean Temperature					X						X					
Mean Diurnal Range	X	X		X							X	X				
Isothermality	X								X		X		X			
Temperature Seasonality			X			X	X	X						X	X	X
Max Temperature of Warmest Month	X	X	X	X	X		X		X	X		X			X	
Min Temperature of Coldest Month	X		X		X		X		X						X	
Temperature Annual Range													X	X		X
Mean Temperature of Wettest Quarter				X								X				
Mean Temperature of Driest Quarter						X			X	X	X		X	X	X	X
Mean Temperature of Warmest Quarter			X													
Mean Temperature of Coldest Quarter		X			X								X			
Annual Precipitation	X		X	X		X				X		X	X	X		X
Precipitation of Wettest Month		X				X	X	X								
Precipitation of Driest Month																
Precipitation Seasonality								X		X						X
Precipitation of Wettest Quarter		X		X	X	X	X	X	X		X	X		X	X	
Precipitation of Driest Quarter																
Precipitation of Warmest Quarter										X						
Precipitation of Coldest Quarter								X								

Once the variable selection was complete, models were tuned to derive the parameters that performed best. The *biomod2* tuning function uses the *ENMeval* package (Kass *et al.*, 2021). Parameters that resulted in the highest True Skill Statistic (TSS) score were retained for the final model runs. The final models were built using these tuned model settings, five repeats of 5 k-fold cross validation for training and test data splits, and five pseudo-absence datasets. This resulted in 131 model runs in total, including model runs where the full dataset was used as training data, and all pseudo-absence datasets. Any models not performing well had the model parameters altered and were then re-run. All models were evaluated with the True Skill Statistic (TSS) and the area under the Receiver Operating Characteristics curve (ROC). ROC is a threshold-independent measure of accuracy and TSS is threshold-dependent. Whilst a third metric of accuracy, Kappa, can be used to evaluate SDMs, it was not used to evaluate these models because it is affected by prevalence (Allouche *et al.*, 2006; McPherson *et al.*, 2004). Model evaluation scores are calculated to assess the ability of the model to predict presences and absences correctly. As each model uses different input variables, these scores cannot be used as an indicator of comparable performance between algorithms. Once satisfied with the performance of these individual models, the full dataset runs for each pseudo-absence dataset were combined into an ensemble model, using a threshold TSS value of 0.6.

Each ensemble model (one for each species and algorithm) was projected over the study area using the observed climate data, generating an ensemble mean, median, committee average, and coefficient of variation. Binary transformed outputs were created using the threshold resulting in the highest TSS score. Models were then projected and binary transformed under four climate change scenarios using 22 CMIP6 models and four RCP-SSP scenarios.

To assess future climate suitability across the range of models and algorithms, the 22 binary GCM projections were summed across each algorithm and warming level and then reclassified into five suitability levels: Very low, Low, Moderate, High, or Very High chance of suitable climate (Table 4.3). By using multiple levels to categorise climate suitability, rather than a binary suitable/unsuitable 'majority rules' approach, it accounts for some of the potential lack of independence between GCMs, where models may have been derived from similar parameters. Using this classification for a given algorithm, a cell with only five

(out of 22) GCMs projecting suitable climate is categorised as having ‘Low’ chance of climate suitability, whereas a cell with 20 GCMs projecting suitable climate is categorised as ‘Very High’. If two or more algorithms classed a cell as ‘high’ or ‘very high’ (15+ GCMs), then that cell was deemed to have suitable climate for the species. This ensures that suitable climate is based upon both climate model and SDM algorithm agreement.

Table 4.3: The reclassification thresholds for assigning each cell to one of five climate suitability metrics. The ‘Number of GCMs’ is the number of projections using each of 22 GCMs which class the cell as climatically suitable.

Number of GCMs	New climate suitability classification
0-4	Very low
5-9	Low
10-14	Moderate
15-18	High
19-22	Very high

Once each cell in the study area was binary transformed for climate suitability at each warming level, areas of internal climate refugia were identified. These areas, within the species’ current geographic range, were classed as climatically suitable in the observed timeframe and all of the projected global warming levels. Internal refugia were compared with the existing protected area network using the World Database on Protected Areas (WDPA; UNEP-WCMC and IUCN, 2024) to highlight whether areas of refugia are within protected areas. Following the least-regrets approach, areas of external climate refugia are not explored in this chapter because they are outside of areas where giraffe currently exist.

4.3 Results

4.3.1 Ensemble model performance

The ensemble models performed well across all algorithms and species, with all TSS scores above 0.8, and all ROC scores above 0.9 (Table 4.4). Sensitivity and specificity were also all high, above 80. There is no ensemble GBM model for Northern giraffe, because individual GBM models did not reach the 0.6 TSS threshold required to show a good ability to generalise to new data. In species where GBM models were included, they performed

highest compared to all other models, whilst Maxent models were the lowest scoring algorithm across all measures for each species.

Table 4.4: Evaluation scores of ensemble models for each species. The highest scores for each metric and species are highlighted in green.

Species	Model algorithm	Binary threshold	Sensitivity	Specificity	TSS	ROC
Northern	GLM	352	99.39	83.00	0.82	0.96
	Maxent	328	84.85	87.65	0.73	0.93
	GAM	606	97.58	91.41	0.89	0.97
Masai	GBM	919	100	99.66	1.00	1.00
	GLM	495	99.57	95.04	0.95	0.99
	Maxent	78	98.27	92.06	0.90	0.98
	GAM	656	98.92	95.76	0.95	0.99
Reticulated	GBM	980	100	100	1.00	1.00
	GLM	566	100	98.08	0.98	1.00
	Maxent	20	99.02	94.04	0.93	0.99
	GAM	798	100	98.59	0.99	1.00
Southern	GBM	990	100	92.24	0.92	0.97
	GLM	557	98.46	90.72	0.89	0.96
	Maxent	231	97.69	84.43	0.82	0.92
	GAM	534	100	90.03	0.90	0.97

4.3.2 Model outputs for observed climate

For each species, the areas projected to be suitable differed depending on the model algorithm used (Figure 4.2). Where GBM models were used, they projected the smallest amount of suitable climate space within the species' range polygon compared to all other models (Table 4.5). For Masai, Reticulated, and Southern species, the Maxent models projected the highest amount of suitable climate area, whilst for Northern giraffe, the GLM model projected the largest area of climate suitability. Differences between models in the percentage of the species' range area projected to be suitable was smallest for Southern giraffe, at 88-98%, closely followed by Northern giraffe at 83-94%, and largest for Reticulated giraffe at 12-100% (Table 4.5).

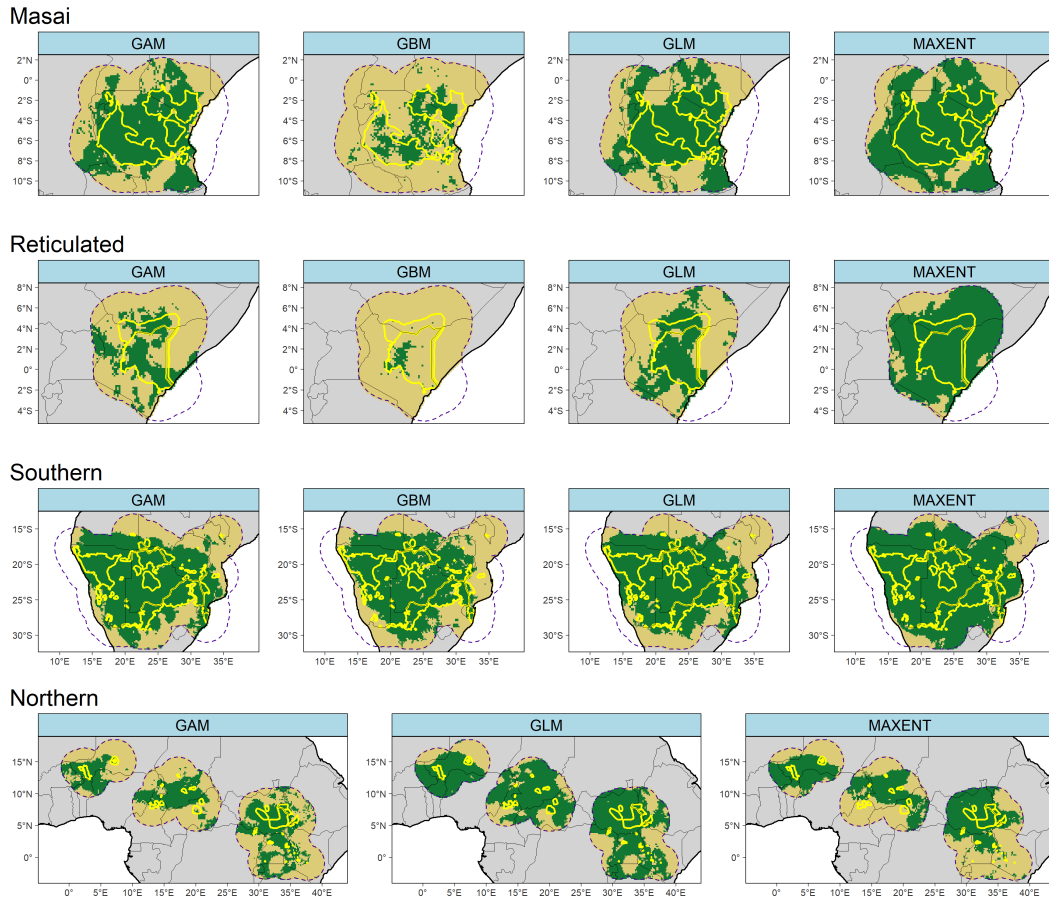


Figure 4.2: The binary transformed outputs for each SDM algorithm projected over each species range for observed climate. Dotted lines show the 300 km buffer around each species' range area, which SDM outputs have been clipped to. Yellow lines show the species' range.

Table 4.5: Count of cells across each species' geographic range where climate is projected to be not suitable (NS) and suitable (S) for each species of giraffe, and for each model algorithm. The percentage of the species' geographic range with suitable climate is shown by the '%' column.

Model	Masai			Northern			Reticulated			Southern		
	NS	S	%	NS	S	%	NS	S	%	NS	S	%
GAM	71	1417	95.23	151	796	84.05	480	645	57.33	107	2907	96.45
GBM	721	767	51.55	–	–	–	985	140	12.44	357	2657	88.16
GLM	109	1379	92.67	55	892	94.19	287	838	74.49	90	2924	97.01
Maxent	33	1455	97.78	158	789	83.32	2	1123	99.82	57	2957	98.11

For Southern and Masai giraffe, when the projections were cropped to the species' range, 86% and 51% of the range, respectively, was projected as suitable climate by all four models

(Figure 4.3). For Reticulated giraffe, only 12% was projected as suitable by all four models. Northern giraffe were only modelled with three algorithms, but all three algorithms project suitable climate in 74% of the cells. At least two models project suitable climate for 98% of the Southern range, 77% of the Reticulated range, 92% of the Northern range, and 97% of the Masai range (Figure 4.3).

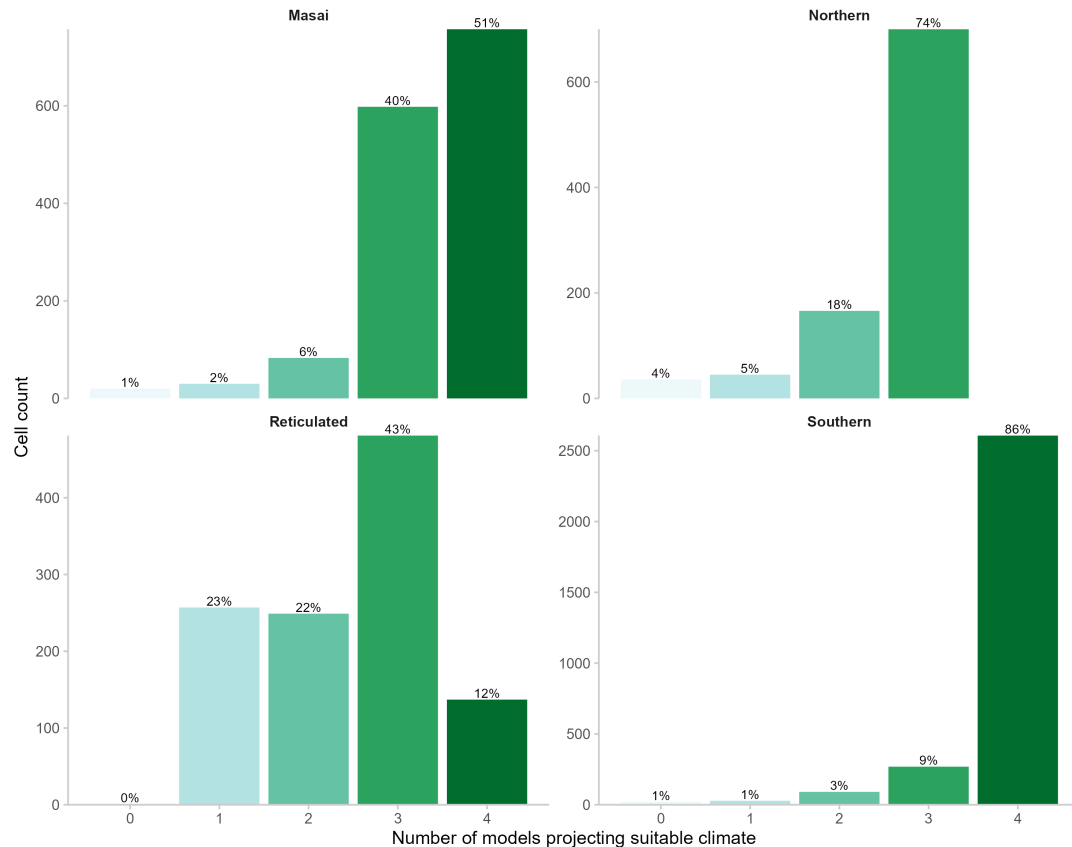


Figure 4.3: The frequency count of cells where n number of models project a suitable climate, for the observed time-period and cropped to the range of each species.

4.3.3 Model outputs for projected climate

Projections of future climate scenarios show that suitable range area is expected to decrease for all four species at each level of warming (Figure 4.4). Under the highest level of warming explored of 3.6°C, all species nonetheless retain areas of suitable climate within their current range polygons. The 300 km range buffer shows how Reticulated and Masai giraffe – the species closest to the equator – are projected to experience range declines, rather than shifts. For Southern and Northern giraffe, however, their suitable climate range area is projected to shift polewards, to the southern and northern parts of their ranges, respectively (Figure 4.4).

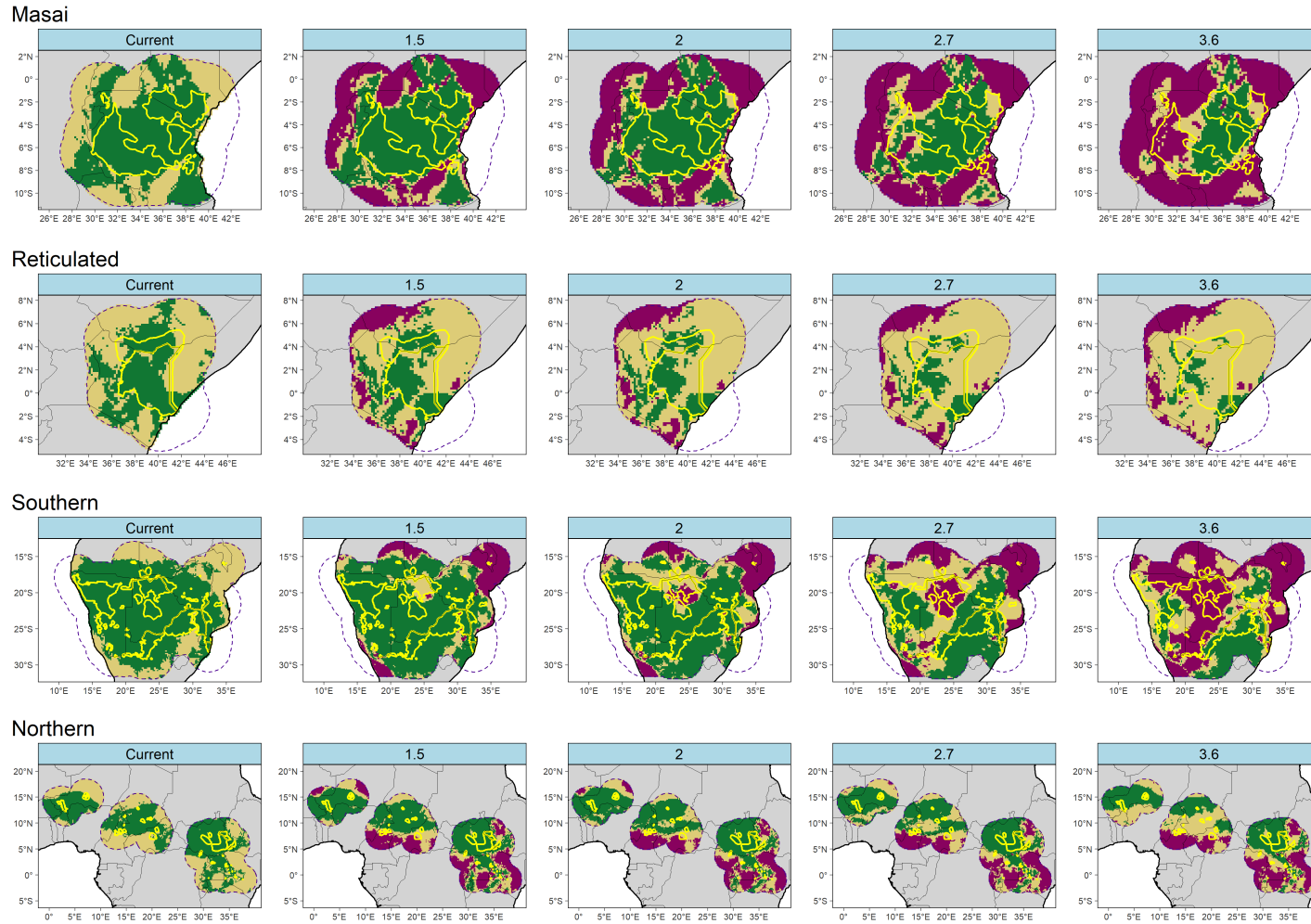


Figure 4.4: Suitable climate area for each species under observed and projected climate scenarios. Green indicates two or more SDMs with high or very high agreement of suitability between GCMs; yellow indicates some agreement between models and GCMs of suitability; purple indicates areas where there was little to no agreement between models or GCMs of suitable climate.

4.3.4 Areas of internal climate refugia

Northern giraffe (*G. camelopardalis*)

Northern giraffe are projected to retain 62% of their current geographic range under all levels of global warming (Table 4.6). When looking at Protected Areas (PAs), only 32% of their range area is refugia within a PA. At three of four warming levels explored, Northern giraffe retain more than 75% of their range as suitable. Refugia for the species is to the westernmost and easternmost parts of the range, with central range area not remaining suitable under the warming levels explored (Figure 4.5).

Table 4.6: The percentage of the Northern giraffe's current geographic range with suitable climate at the given warming level. 'Cumulative suitable climate' refers to an area which is projected to have suitable climate at the given warming level and all previous warming levels. This is different from 'Suitable climate', which is a snapshot of percentage suitability at the given warming level and may include newly suitable areas due to climate shifts. The 'Cumulative suitable climate' at 3.6°C represents the percentage of the species' geographic range which is internal climate refugia. 'Cumulative suitable climate & PA' are areas of cumulative suitability and PA status, as defined by the WDPA dataset (UNEP-WCMC and IUCN, 2024).

Warming level	% species' geographic range		
	Suitable climate	Cumulative suitable climate	Cumulative suitable climate & PA
Observed	91.4	91.4	57.3
1.5°C	82.5	81.4	50.1
2°C	83.2	79.8	48.5
2.7°C	81.0	75.7	44.6
3.6°C	63.1	62.1	32.0

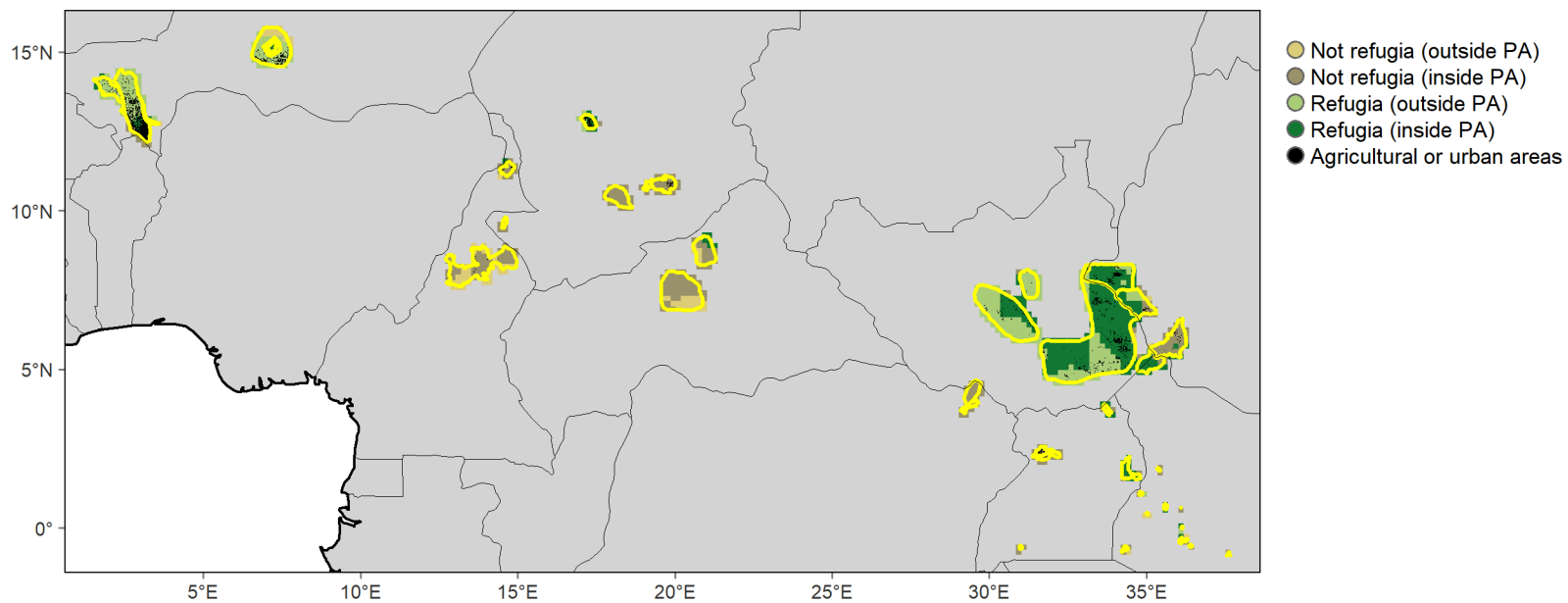


Figure 4.5: Areas of internal climate refugia for Northern giraffe (green). The species' geographic range is outlined in yellow and shaded areas are those within protected areas, based on the WDPA (UNEP-WCMC and IUCN, 2024). Black areas indicate agricultural or urban areas at a resolution of 300 m using land cover data downloaded from the Copernicus Climate Change Service, Climate Data Store (2019).

Masai giraffe (*G. tippelskirchi*)

Masai giraffe retain 41% of their current range as internal climate refugia, but only 33% of their range is both refugia and within a PA (Figure 4.6, Table 4.7). Most of the central-eastern portion of the range remains suitable, whilst the western portion and furthest eastern portions are not suitable across all warming scenarios. The areas of internal climate refugia are found towards the eastern and central areas of their current geographic range.

Table 4.7: The percentage of the Masai giraffe's current geographic range with suitable climate at the given warming level. 'Cumulative suitable climate' refers to an area which is projected to have suitable climate at the given warming level and all previous warming levels. This is different from 'Suitable climate', which is a snapshot of percentage suitability at the given warming level and may include newly suitable areas due to climate shifts. The 'Cumulative suitable climate' at 3.6°C represents the percentage of the species' geographic range which is internal climate refugia. 'Cumulative suitable climate & PA' are areas of cumulative suitability and PA status, as defined by the WDPA dataset (UNEP-WCMC and IUCN, 2024).

Warming level	% species' geographic range		
	Suitable climate	Cumulative suitable climate	Cumulative suitable climate & PA
Observed	96.7	96.7	77.1
1.5°C	91.5	91.4	73.4
2°C	84.5	84.2	68.7
2.7°C	63.2	62.8	51.8
3.6°C	41.6	41.4	33.1

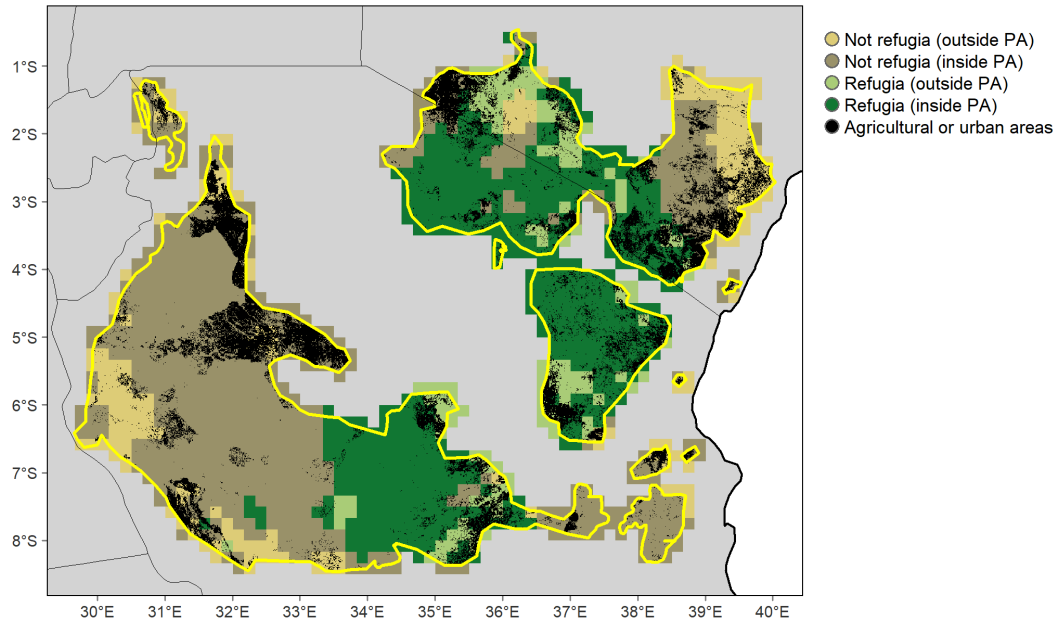


Figure 4.6: Areas of internal climate refugia for Masai giraffe (green). The species' geographic range is outlined in yellow and shaded areas are those within protected areas, based on the WDPA (UNEP-WCMC and IUCN, 2024). Black areas indicate agricultural or urban areas at a resolution of 300 m using land cover data downloaded from the Copernicus Climate Change Service, Climate Data Store (2019).

Reticulated giraffe (*G. reticulata*)

Reticulated giraffe retain suitable climate in 24% of their geographic range across all levels of warming, with only ~14% of their range being both internal climatic refugia and within a PA (Table 4.8). Within Kenya, areas of internal climate refugia are found in the western and northern parts of their current geographic range, with some overlap with PAs (Figure 4.7).

Table 4.8: The percentage of the Reticulated giraffe's current geographic range with suitable climate at the given warming level. 'Cumulative suitable climate' refers to an area which is projected to have suitable climate at the given warming level and all previous warming levels. This is different from 'Suitable climate', which is a snapshot of percentage suitability at the given warming level and may include newly suitable areas due to climate shifts. The 'Cumulative suitable climate' at 3.6°C represents the percentage of the species' geographic range which is internal climate refugia. 'Cumulative suitable climate & PA' are areas of cumulative suitability and PA status, as defined by the WDPA dataset (UNEP-WCMC and IUCN, 2024).

Warming level	% species' geographic range		
	Suitable climate	Cumulative suitable climate	Cumulative suitable climate & PA
Observed	77.0	77.0	31.4
1.5°C	58.7	58.2	27.2
2°C	50.2	49.6	24.4
2.7°C	38.1	37.4	20.1
3.6°C	24.8	24.2	13.6

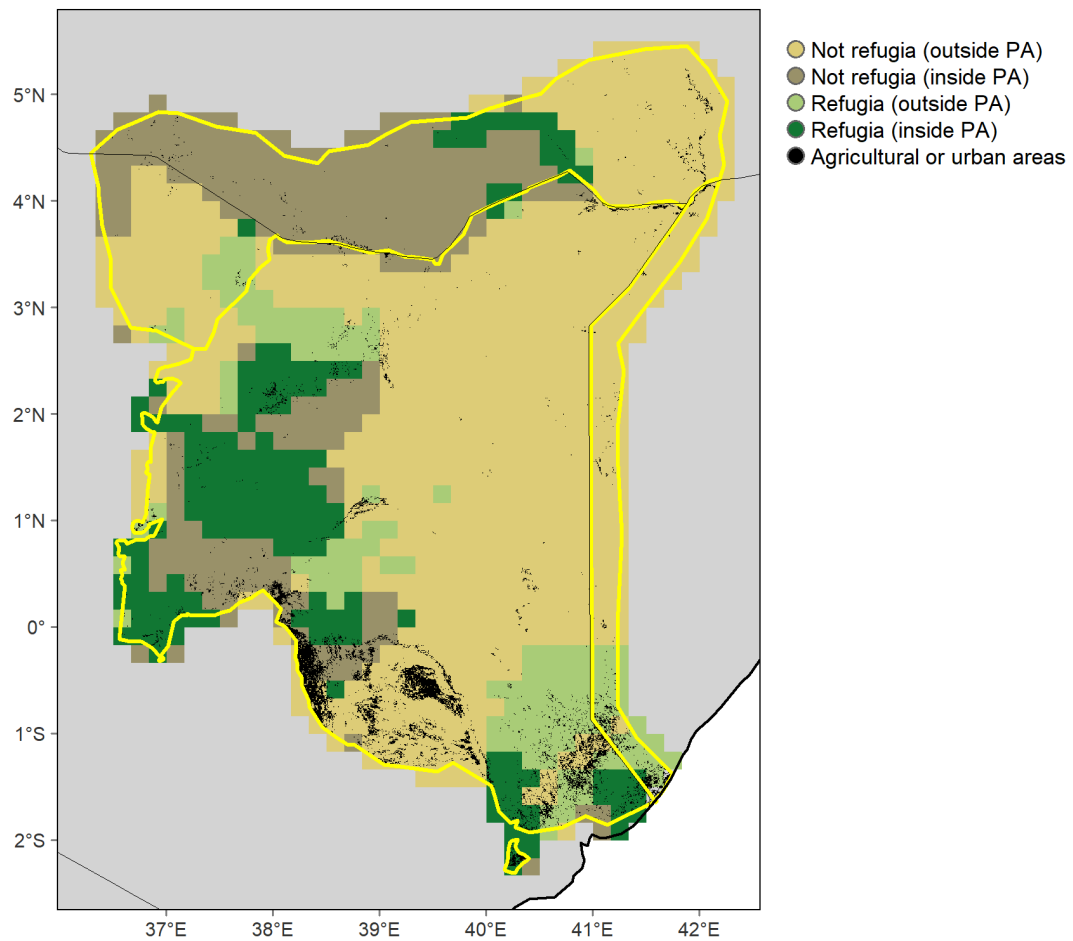


Figure 4.7: Areas of internal climate refugia for Reticulated giraffe (green). The species' geographic range is outlined in yellow and shaded areas are those within protected areas, based on the WDPA (UNEP-WCMC and IUCN, 2024). Black areas indicate agricultural or urban areas at a resolution of 300 m using land cover data downloaded from the Copernicus Climate Change Service, Climate Data Store (2019).

Southern giraffe (*G. giraffa*)

Across all levels of warming, 30% of the Southern giraffe's current geographic range is projected to be internal climate refugia, but only ~14% of the range is refugia within PAs (Table 4.9). Within Botswana, there are no areas of internal climate refugia for Southern giraffe – internal climate refugia are mostly found within South Africa and Namibia (Figure 4.8).

Table 4.9: The percentage of the Southern giraffe’s current geographic range with suitable climate at the given warming level. ‘Cumulative suitable climate’ refers to an area which is projected to have suitable climate at the given warming level and all previous warming levels. This is different from ‘Suitable climate’, which is a snapshot of percentage suitability at the given warming level and may include newly suitable areas due to climate shifts. The ‘Cumulative suitable climate’ at 3.6°C represents the percentage of the species’ geographic range which is internal climate refugia. ‘Cumulative suitable climate & PA’ are areas of cumulative suitability and PA status, as defined by the WDPA dataset (UNEP-WCMC and IUCN, 2024).

Warming level	% species’ geographic range		
	Suitable climate	Cumulative suitable climate	Cumulative suitable climate & PA
Observed	98.4	98.4	61.4
1.5°C	88.8	88.2	54.4
2°C	74.8	74.1	42.0
2.7°C	54.3	53.7	27.5
3.6°C	30.8	30.2	13.8

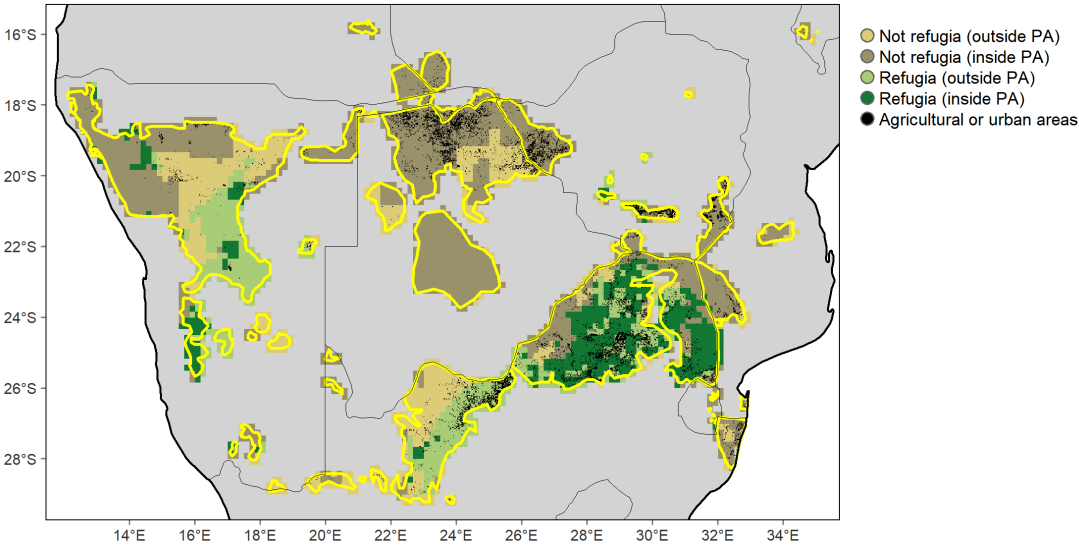


Figure 4.8: Areas of internal climate refugia for Southern giraffe (green). The species’ geographic range is outlined in yellow and shaded areas are those within protected areas, based on the WDPA (UNEP-WCMC and IUCN, 2024). Black areas indicate agricultural or urban areas at a resolution of 300 m using land cover data downloaded from the Copernicus Climate Change Service, Climate Data Store (2019).

4.4 Discussion

Given the uncertainties surrounding future warming levels, the identification of climate refugia is an important conservation tool. It offers a 'least-regrets' approach for conservation decision-makers, aiding in spatial prioritisation to enhance the long-term success of present-day conservation actions by minimising the risk of investing resources in measures that may become ineffective if realised climatic conditions differ from projections. In this research, key areas of climate refugia for each species of giraffe were identified, both within and outside of protected areas. The research shows that there are projected to be areas of suitable climate remaining for each species, even at the highest levels of warming, but that the amount of suitable area differs between species. The research accounts for a range of projected warming level scenarios but highlights the clear conservation benefits of limiting global warming to less than 2°C, at which each species would retain at least 50% (50 - 84%) of their current range area as suitable climate.

Four SDM algorithms were used in this research to account for uncertainties in model performance and variable selection. All models performed well, with the exception of the GBM model for Northern giraffe which did not pass initial threshold tests and was consequently not used. Maxent models consistently projected the largest amount of suitable range area, but they performed worse than GLM, GAM, and GBM algorithms across all evaluation metrics used. Despite this, the results do not necessarily reflect differences in model algorithm predictive performance because of the different environmental variables used for each model, which could be the source of discrepancies. Higher performing evaluation scores in other models could indicate superior variable selection at earlier stages, or possible model overfitting. GBM models consistently projected the lowest amount of suitable range area, showing potential model overfitting. This has few implications for the interpretation of the results, however, because areas of refugia were based on a majority, rather than full model agreement.

Due to the human-induced range decline of giraffe over the last few decades, the models in this chapter may represent a narrower climatic niche than that of each giraffe species. Martínez-Freiría *et al.* (2016) demonstrated the importance of modelling historical occurrence and climate data in giraffe SDMs to account for the effects of human-induced range reduction on the projected suitable climate. They showed that historical models

projected around 40% larger areas of climate suitability compared to using only contemporary records. This approach was deemed unsuitable for the models in this chapter; due to the recently updated four-species taxonomy; it was not possible to definitely assign historical occurrence records to the correct species. This issue was particularly apparent in areas where species' ranges are adjacent, such as in Kenya, where the Northern, Masai, and Reticulated giraffe ranges are in close proximity. Additionally, if genetic variation has been lost alongside the human-induced range and population declines, some local adaptations to these historical range areas may no longer exist. The sensitivity analysis presented in the Supplementary Material assessed the potential influence of including historical occurrence data, assuming that all historical areas have remained climatically suitable and that all range declines are entirely human-induced. For Masai, Southern, and Reticulated giraffe, the inclusion of historical records resulted in minimal changes to projected climate suitability. Northern giraffe showed more pronounced differences, with a higher proportion of their current geographic range projected as climatically suitable under all warming scenarios. While human-induced range reduction may have influenced the outputs, this effect is small for three species. Importantly, the key conclusions presented here remain the same because they focus on internal climate refugia, which are largely consistent in the main models and sensitivity models. Additionally, because the sensitivity analysis generally projected slightly larger areas of internal climate refugia, the refugia estimated in the main models can be regarded as cautionary and conservative, which aligns with the least-regrets approach taken in this chapter. Given the limited influence of historical range inclusion on the results and the consistency of the main conclusions, the original modelling framework was considered appropriate for use in the remainder of the thesis, without revision. Nonetheless, from a conservation standpoint it is important to note that range edges may be more suitable than projected within the models. Whilst the aim of Martínez-Freiría *et al.*'s (2016) research was not specifically to identify areas for conservation, results from both studies show an optimistic outlook for giraffe as large amounts of range area are projected to remain climatically suitable under multiple global warming levels.

The research in this chapter shows the importance of up-to-date taxonomic status for species-specific modelling when projecting climate suitability across warming levels. When projected across Africa, the models rarely projected suitable climate in the same

areas for multiple species (shown on the 'climate suitability' page of the GiraffeClim application, discussed in Chapter 6). Northern giraffe have a highly fragmented range, consisting of three subspecies ranging from 'Vulnerable' to 'Critically Endangered' (Muller *et al.*, 2018). This species was projected to have the smallest percentage range loss at the highest levels of warming, but areas of range loss are focused on the central part of the range, belonging to the Critically Endangered Kordofan subspecies. Conversely, Southern giraffe are projected to see the largest percentage range loss, but are currently the species with the largest population (Brown *et al.*, 2021), with the assessed subspecies categorised as 'Least Concern'. Whilst this species may not be a current conservation priority, the models show that suitable climate area is projected to move poleward, and that increased warming is projected to cause limited suitable range area within Botswana. Masai and Reticulated giraffe are both projected to lose ~50% of their climatic range under the highest levels of warming, with Masai giraffe losing range area in western Tanzania, and Reticulated giraffe being restricted to range areas in central Kenya.

Protected Areas (PAs) have long been at the forefront of conservation practices, but with a changing climate, some have suggested that the spatial rigidity of PAs may hinder conservation, blocking species from tracking their suitable climate (Araújo *et al.*, 2004). Others have found that PAs facilitate range expansion, acting as 'stepping stones' in a fragmented landscape (Thomas and Gillingham, 2015). Regardless of range changes, the research shows that PAs maintain an important role in the conservation of giraffe, safeguarding areas of internal climate refugia. More than 50% of refugia are located within a protected area for Northern, Masai, and Reticulated giraffe, and just under 50% (46%) is within a PA for Southern giraffe. These PAs span multiple levels of protection and include areas such as Community Conservancies. It is important to note, however, that the efficacy of PAs in sustaining giraffe populations is heavily linked to law enforcement activity, without which, giraffe populations would likely decline (Bond *et al.*, 2023).

The approach of identifying refugia for climate-change resilient conservation has gained traction over the last few decades (Keppel *et al.*, 2012). This research looks at macroclimate refugia over a large scale, but it is possible that giraffe could persist in current range areas that are projected to become unsuitable, through the use of microclimate refugia (Nadeau *et al.*, 2022). These microrefugia can maintain favourable climate conditions, usually due

to topographic factors, which allow species to persist despite unfavourable climate at larger scales. However, these areas would be, by nature, smaller in size and therefore only able to support small giraffe populations. Additionally, if this climate suitability is maintained through topography, the terrain may be unsuitable for giraffe to travel on. Due to the distances travelled by giraffe and the size of the species, this chapter focused on macroclimate refugia, but an investigation into climate trends at finer resolutions may aid in understanding the impact of climate change on these species. Similarly, the application of an agricultural and urban land mask has enabled the examination of refugia suitability at a finer scale, ruling out unsuitable land types. There are nonetheless further nuances that affect the suitability of these areas of refugia at finer scales, such as water availability, habitat heterogeneity, topography, and species interactions. As such, this research should act as a starting point for assessing long-term spatial suitability, where conservationists can apply their on-the-ground knowledge to further ascertain suitability.

4.5 Conclusion

Understanding the potential future impact of climate change on species is essential in making present-day conservation decisions with the highest chance of long-term success. The areas of refugia highlighted in this study should be considered a conservation priority, and act as choices of 'least regrets' for conservation decision-makers given the uncertainty of future climate change projections. Importantly, many areas of internal climate refugia overlap with existing protected areas, highlighting the relevance of protected areas to climate-informed giraffe conservation. These areas should be monitored to ensure effective management and strong enforcement, where appropriate. Whilst the focus of this chapter has been macroclimate refugia, the importance of microrefugia is not ignored; instead, it is suggested that both approaches are used in tandem, with knowledge of macrorefugia guiding finer-scale assessments on the ground to fully understand the nuances that make an area suitable for giraffe. As a whole, this research has shown a somewhat positive outlook for giraffe; all four species retain areas of suitable climate even at the highest global warming level explored of 3.6°C.

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Supplementary Material

This section contains the supplementary material for Chapter 4 ‘Identifying areas of climate change refugia as a least regrets conservation strategy for giraffe species’.

Including historical occurrence data in species distribution models

To assess the potential influence of human-induced range decline on the species distribution models (SDMs) presented in Chapter 4, each SDM was re-run with historical occurrence records incorporated into the occurrence dataset. Models were fitted using identical model algorithms, parameters, and environmental predictors, with the only differences being the inclusion of historical occurrence records obtained from Martínez-Freiría *et al.* (2016), and the regeneration of pseudo-absence points to ensure no overlap with the expanded occurrence dataset. Pseudo-absences were generated following the same procedures described in Chapter 4, Section 4.2.3 ‘Pseudo-absence data’. The models were run with the same 1970-2000 climate data, so they represent a scenario where each species’ range contractions are solely human-induced, without any climate-induced range reduction. Therefore, areas of historical occurrence are assumed to have remained climatically suitable under current conditions.

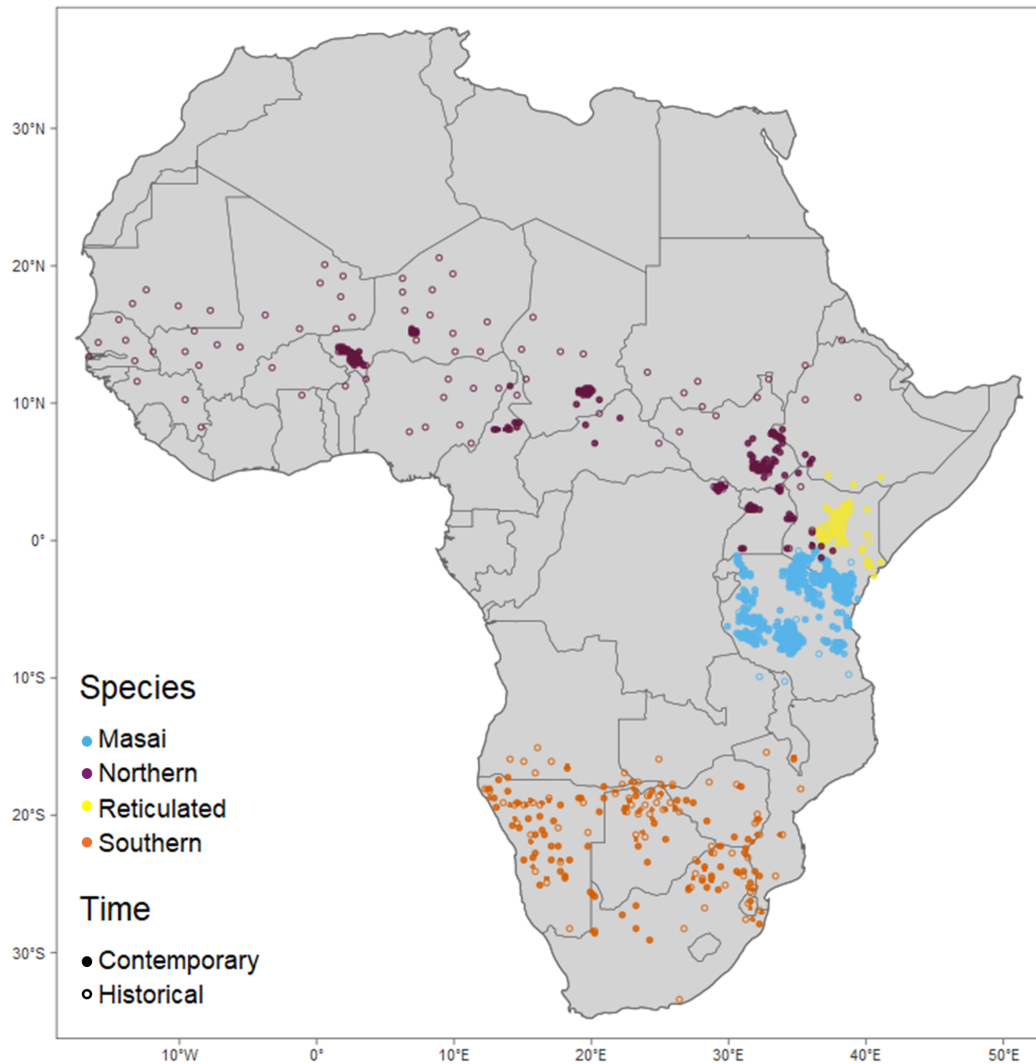


Figure S4.1: The occurrence points used to generate species distribution models (SDMs) for each species of giraffe. Solid dots indicate occurrence records used in the main contemporary SDMs, and open dots are the historical records used to generate the sensitivity SDMs in this supplementary material.

Overall, the inclusion of historical occurrence data resulted in minimal changes to projected climate suitability for Masai, Southern, and Reticulated giraffe. In contrast, Northern giraffe exhibited more pronounced differences, with a greater proportion of their geographic range projected to be climatically suitable across multiple global warming scenarios (Figure S4.2, Table S4.1). Under the highest warming scenario of 3.6°C, each species maintained at least 14.7% of its range as climate refugia (Table S4.1), compared to 13.6% in models without historical occurrence data (Tables 4.6 - 4.9). The areas of refugia overlap largely with the core SDM models, with at least 85% of refugia also showing as refugia in models incorporating historical occurrence records (Table S4.2).

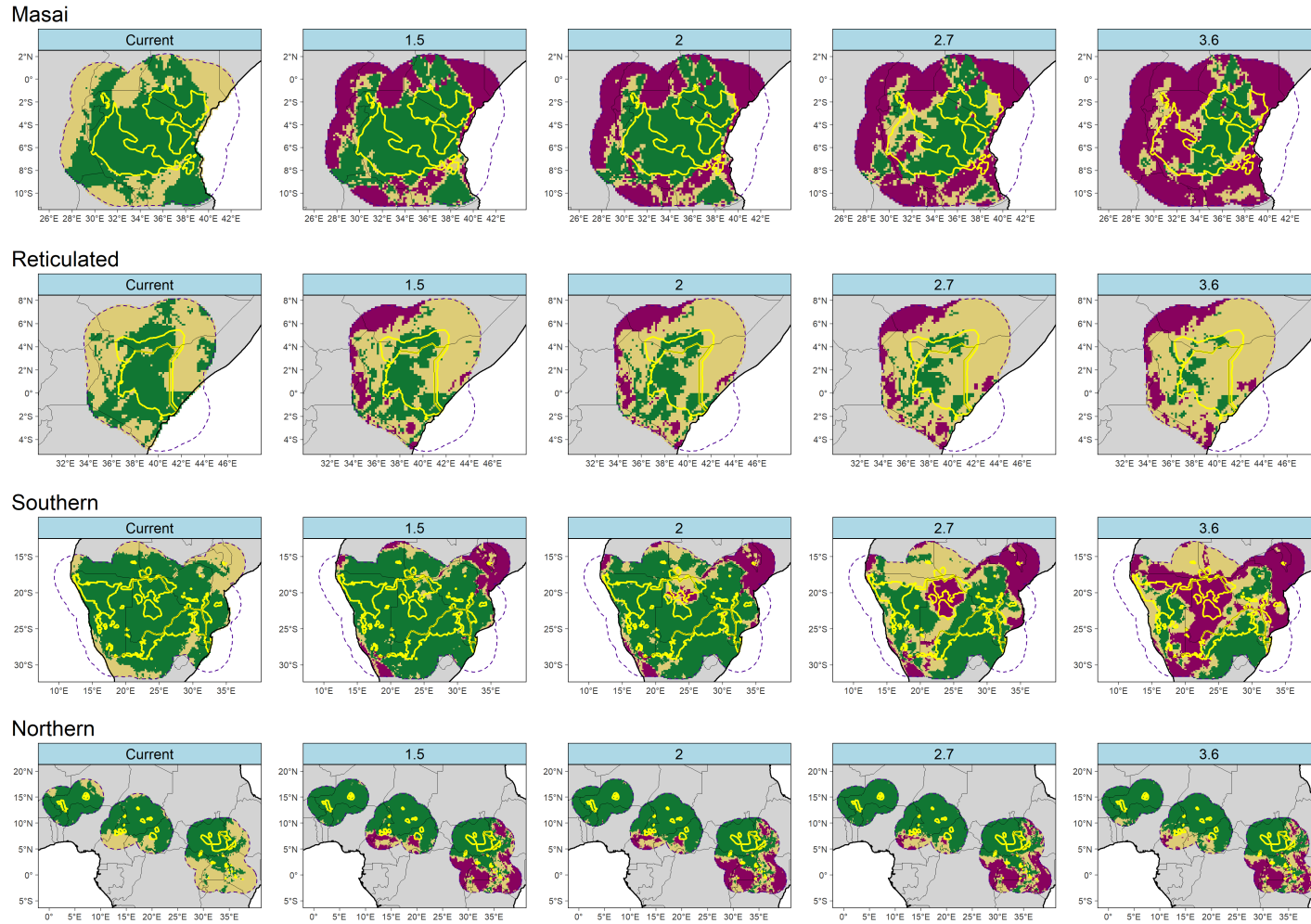


Figure S4.2: Suitable climate area for each species under observed and projected climate scenarios, modelled using species distribution models which integrated historical occurrence data alongside contemporary data for each species of giraffe. Green indicates two or more SDMs with high or very high agreement of suitability between GCMs; yellow indicates some agreement between models and GCMs of suitability; purple indicates areas where there was little to no agreement between models or GCMs of suitable climate. Species geographic range outlines are shown in bright yellow.

Table S4.1: Projected suitable and cumulative suitable climate within each species' geographic range, expressed as a percentage of range, with absolute change (percentage points) relative to contemporary-only SDMs shown in parentheses. Suitable climate is the percentage of the species' geographic range considered climatically suitable at each warming level. Cumulative suitable climate refers to areas suitable at the given warming level and all previous warming levels.

Warming level	% species' geographic range		
	Suitable climate	Cumulative suitable climate	Cumulative suitable climate & PA
Northern giraffe			
Observed	94.3 (+2.9)	94.3 (+2.9)	58.7 (+1.41)
1.5°C	93.3 (+10.85)	92.9 (+11.53)	57.3 (+7.24)
2°C	94.4 (+11.2)	92.6 (+12.81)	57 (+8.52)
2.7°C	94.3 (+13.3)	92.4 (+16.7)	56.9 (+12.32)
3.6°C	89.4 (+26.34)	89.1 (+27.02)	54.6 (+22.59)
Masai giraffe			
Observed	96.8 (+0.14)	96.8 (+0.14)	76.9 (-0.17)
1.5°C	91.9 (+0.43)	91.7 (+0.33)	73.3 (-0.1)
2°C	86.7 (+2.18)	86.1 (+1.88)	69.9 (+1.24)
2.7°C	62.4 (-0.79)	61.8 (-1.0)	50.3 (-1.5)
3.6°C	43 (+1.37)	42.6 (+1.24)	34.3 (+1.2)
Reticulated giraffe			
Observed	81.2 (+4.18)	81.2 (+4.18)	31.4 (+0)
1.5°C	62.9 (+4.19)	62.5 (+4.33)	27.2 (+0.01)
2°C	53.4 (+3.23)	53 (+3.39)	25.2 (+0.76)
2.7°C	40 (+1.86)	39.4 (+2.03)	21.5 (+1.4)
3.6°C	26.5 (+1.69)	25.9 (+1.67)	15.6 (+2.01)
Southern giraffe			
Observed	99.2 (+0.83)	99.2 (+0.83)	61.9 (+0.48)
1.5°C	95.9 (+7.1)	95.7 (+7.47)	59.1 (+4.71)
2°C	83.2 (+8.44)	83 (+8.91)	49.8 (+7.82)
2.7°C	59.8 (+5.48)	59.4 (+5.71)	30.8 (+3.26)
3.6°C	33.8 (+2.99)	33.6 (+3.39)	14.7 (+0.93)

Table S4.2: The percentage of refugia from contemporary SDM models in the main chapter that is retained when historical occurrence data are included in the models. Retention is compared at an Africa-wide scale (Refugia overlap), and within the species' current geographic range (Internal refugia overlap).

Species	Refugia overlap (%)	Internal refugia overlap (%)
Masai	94.28	97.72
Reticulated	85.04	89.02
Southern	95.41	94.43
Northern	93.94	100.00

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Martínez-Freiría, F., Tarroso, P., Rebelo, H. and Brito, J.C., 2016. Contemporary niche contraction affects climate change predictions for elephants and giraffes, *Diversity and Distributions*, 22(4), pp. 432–444. Available at: <https://doi.org/10.1111/ddi.12406>.

Beyond mean climate: A comprehensive approach to prioritising areas for giraffe conservation under climate change

Abstract

Climate change-informed planning is essential to maximise the long-term success of present day conservation actions. Many studies focus on shifts in species' climate suitability, but whilst important, this focus overlooks many other potential impacts of climate change. When assessing a species' risk and planning climate-informed conservation actions for giraffe, it is crucial to consider both direct and indirect climate impacts, such as extreme weather events not captured in projections of changes in mean climate, as well as co-occurring anthropogenic threats that may unfold over the same time frame. The decline of giraffe populations over recent decades and the limited resources available for conservation increase the need for targeted conservation actions which aim to minimise long term threats. To identify the areas for giraffe that are projected to be least impacted by climate change and anthropogenic impacts, Zonation software was used to spatially prioritise areas under observed and projected climate. For each climate scenario, priority areas maximise projections of available food species richness and suitable climate

for giraffe, whilst minimising the human modification of land and projected presence of predators, duration of extreme climatic events, and human population. These priority rankings were calculated across the current geographic ranges of each giraffe species and subspecies, as well as extending the analysis to areas of external climate refugia to account for possible range shifts. The outputs were compared to protected area distribution and management type, and areas of high priority across multiple warming levels were identified. An additional ecological stability analysis was performed to identify which areas are exposed to the least negative change in input factors at the highest warming levels. The results showed that while many high-ranking priority areas fall within the existing protected area network, key areas remain unprotected. Where low ranking cells have dispersal barriers which prohibit the movement of giraffe, these areas should be considered for increased adaptation efforts to mitigate the high projected impacts to giraffe. These results help to identify areas for potential conservation translocations and candidates for protected area expansion whilst providing an insight into which areas may need increased adaptation effort under different levels of global warming.

5.1 Introduction

Species conservation planning is increasingly incorporating research on the projected impacts of climate change (Cross *et al.*, 2012; Groves *et al.*, 2012; McLaughlin *et al.*, 2022; Hannah and Midgley, 2023). Much of this research still focuses on long-term mean climate changes and its projected effects on species distributions (Jones *et al.*, 2016). However, the potential impacts of climate change on biodiversity are multi-faceted (Bellard *et al.*, 2012). Species are also vulnerable to negative changes in extreme climate events (Bailey and van de Pol, 2016), such as droughts, and indirect effects mediated through disruptions in biotic interactions (Gilman *et al.*, 2010). For example, uneven shifts in the geographic distribution of predators and prey may have implications for both species. Conservation planning for threatened species needs to account for these multifaceted impacts of climate change. Moreover, climate change does not occur in isolation. Increasing human population growth, land-use change, and habitat conversion are likely to interact with climatic stressors and compound threats to biodiversity (IPBES, 2019). When assessing a species' risk from climate change, it is therefore critical to consider both direct and indirect

impacts from climate change, alongside co-occurring non-climatic, anthropogenic threats.

Giraffe (*Giraffa* spp.) are highly charismatic species currently found in 21 countries across Sub-Saharan Africa (O'Connor *et al.*, 2019). The four species of giraffe and their subspecies have geographically distinct ranges and differing threatened statuses, varying from 'Least Concern' to 'Critically Endangered' (Muller *et al.*, 2018). To aid in conservation planning, areas of climate change refugia have been identified for each species of giraffe, using projections of mean climate at global warming levels of up to 3.6°C (see Chapter 4). However, giraffe populations are impacted by additional anthropogenic and climatic pressures. Historical declines have largely resulted from poaching, habitat loss, and fragmentation (Muller *et al.*, 2018), whilst natural predation from lions and periods of drought have also caused population reductions (Strauss *et al.*, 2015; Muller *et al.*, 2018). In addition to these threats, giraffe have a varied diet and rely on access to specific forage species, predominantly *Vachellia* and *Senegalia* spp. (previously termed *Acacia* spp.) which may also be affected by climate and land-use change in the future.

Projections indicate that both climatic and non-climatic pressures on giraffe are likely to worsen at the warming levels used to project suitable climate for giraffe in Chapter 4. Climate models project that higher global warming levels are likely to cause increases in the duration and intensity of meteorological drought conditions across southern and western Africa (Ukkola *et al.*, 2020). Alongside this, the human population in Sub-Saharan Africa is projected to almost triple by 2100 (Figure 5.1; UN DESA, 2024), with implications for increased poaching, habitat loss and fragmentation (Meyer and Turner, 1992; Lindsey *et al.*, 2013).

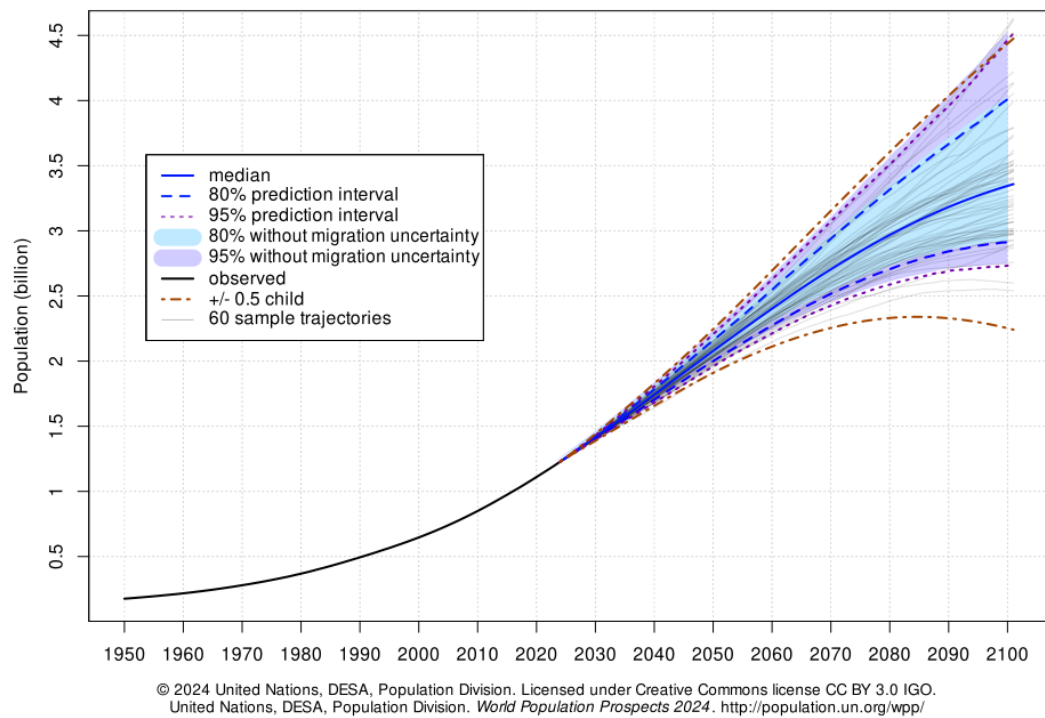


Figure 5.1: Observed and projected total human population count in Sub-Saharan Africa up to 2100, modified from the United Nations Department of Economic and Social Affairs (UN DESA), Population Division (2024).

These projected changes to both climatic and non-climatic anthropogenic pressures highlight the urgent need for conservation planning approaches that integrate multiple threats. One such approach is spatial conservation prioritisation, which offers a quantitative, systematic framework for identifying key areas for biodiversity, where conservation actions can be most effective. Spatial prioritisation tools have been widely used to map priority areas for protected area (PA) expansion, habitat restoration, and biodiversity offsetting (Moilanen, 2012; Moilanen *et al.*, 2022). These tools can incorporate a wide variety of input data, such as species richness, climate suitability, and human population metrics, allowing for transparent trade-off analyses and informed conservation decisions (Tallis *et al.*, 2021). Given the many threats faced by giraffe from both climatic and anthropogenic factors, spatial prioritisation offers a critical opportunity to identify areas where risks are minimised, but key ecological resources and climate suitability are retained. Outputs from such analyses can help guide present-day conservation decisions, including PA expansion, restoration efforts, or in-situ adaptation planning. By identifying

these areas now, conservation strategies can be aligned with long-term species viability under multiple plausible future scenarios.

The aim of this chapter is to identify priority areas for the conservation of each giraffe species and subspecies under projected climatic and non-climatic anthropogenic impacts. These areas should represent the best available balance within each (sub)species' geographic range based on climate suitability, resource availability, and potential threats. Spatial priorities will be assessed under multiple global warming scenarios and timeframes to guide conservation efforts that are adaptive, forward-looking, and responsive to different levels of climate change. By doing so, this approach supports strategic decision-making that enhances giraffe resilience and long-term population viability.

5.2 Methods

5.2.1 Choosing spatial prioritisation software

Spatial prioritisation software can be used to identify areas which maximise positive inputs and minimise negative inputs within a landscape. Negative inputs are often referred to as 'costs' and this can mean either a financial cost (for example, the cost of buying land for conservation) or an undesirable feature, such as the presence and severity of a threat to a species. Two examples of prioritisation software commonly used in the conservation sector are Marxan (Ball *et al.*, 2009) and Zonation (Moilanen *et al.*, 2022). These two programs differ in the optimisation approach used to identify priority cells. Marxan uses a 'minimum-set' approach, where a portfolio of cells is identified that meets the conservation goal at the lowest possible cost level (usually a financial cost). Because of this, Marxan is commonly used to identify fixed spatial areas, such as in protected area planning. Zonation, on the other hand, uses a 'maximum-cover' approach which produces a hierarchical priority ranking across the entire study extent, ranking cells continuously from 0 - 1. To create this ranking, the least valuable cells within the landscape are removed one by one, based on the marginal loss of conservation value (explained further in section 5.2.2 below). This results in the highest-scoring priority cells maximising the positive features relative to the negative features. Zonation outputs are therefore more flexible than Marxan outputs, not requiring pre-defined targets.

Research comparing Marxan and Zonation found that high priority outputs are largely similar (Delavenne *et al.*, 2012), but the utility of each depends on the aim of the research. For this chapter, a hierarchical ranking across the entire study extent is preferable in comparison to Marxan's minimum-set approach. This is because it allows for the direct comparison of each cell in the (sub)species' geographic range, highlighting both the best areas which balance resources, suitable climate, and threats, but also those which may need the most adaptation effort to remain suitable for giraffe. For this reason, Zonation 5 (v2.0.2) (Moilanen *et al.*, 2022) was used in this analysis.

5.2.2 Marginal loss rule

Because Zonation analyses often have multiple input features (either positive or negative), there are several ways of determining the total conservation value (marginal loss; ML) of a cell. Zonation software employs a Marginal Loss Rule (MLR) to determine the aggregate value of each cell in the landscape, and therefore its priority ranking. The MLR is defined by the user, but there are several predefined options. The two main choices for MLR are the Additive Benefit Function (ABF) and Core Area Zonation (CAZ). In both cases, Zonation first standardises the values of each feature across the landscape to 1, such that the value of a feature within a specific cell represents the proportion of that feature's total distribution across the landscape. The MLR is then used to determine the least valuable cell in the landscape, which is then removed (given the lowest rank). Zonation does this iteratively, removing the lowest scoring cell from the landscape, re-standardising the remaining cells and recalculating the ML of each cell, until all cells have a priority ranking.

The MLR for ABF applies a diminishing returns transformation to each feature using a power function, before summing them. The CAZ algorithm, specifically 'CAZ2', calculates the root sum of squares. Whilst both of these MLR algorithms could help identify priority areas for giraffe conservation, the CAZ2 method was chosen for the analysis in this chapter. CAZ2 ensures that, whilst taking into account the value of each feature, features which are worst off in the landscape have a slight emphasis. This is particularly useful in terms of removing negative features from the landscape early on in the priority rankings.

Under CAZ2, the ML value M of each cell i is calculated as the difference between the contribution from positively weighted features, M_{iP} , and negatively weighted features,

M_{iN} :

$$M_i = M_{iP} - M_{iN}$$

The positive contribution, M_{iP} is found by:

$$M_{iP} = \left(\sum_{j=1}^n (w_j r_{ij})^2 \right)^{1/2}$$

Where w_j is the weight assigned to positive feature j (see section 5.2.6 ‘Zonation weightings’), and r_{ij} is the fraction of total remaining distribution of feature j located in cell i .

The negative contribution is calculated similarly, but takes into account the proportion of the feature remaining in the cell compared to what has already been removed:

$$M_{iN} = \left(\sum_{k=1}^n \left(w_k \cdot \frac{p_{ik}}{1 - r_k + p_{ik}} \right)^2 \right)^{1/2}$$

Where p_{ik} is the fraction of original occurrences of negative feature k in cell i (before any cell removal iterations) and r_k is the fraction of feature k which remains in the landscape for the given iteration.

To understand the impact on priority rankings of using CAZ2 compared to ABF, all Zonation analyses were run additionally using ABF. From these outputs, the extent of overlap of high priority areas was calculated, alongside the mean absolute difference of priority rankings. These outputs can be found in the supplementary material.

5.2.3 Study area

Zonation analyses were performed separately for each giraffe species and subspecies, with the exception of the Luangwa subspecies which was not included due to a lack of climate suitability information and small range size. The primary study area in each analysis was defined by the (sub)species’ current geographic range, using range maps provided by the Giraffe Conservation Foundation (Figure 5.2). This allowed for the identification of priority

areas within existing distributions, highlighting locations which are most favourable for giraffe at each warming level, whilst also identifying low ranking areas which may need higher adaptation effort to remain viable for giraffe in the future.

However, some areas important for long-term conservation may lie outside species' current geographic ranges, in areas of external climate refugia. For Northern, Southern, and Masai giraffe, projections from Chapter 4 indicate the presence of climate refugia beyond their existing range. As with the previous chapter, climate refugia are defined in this chapter to mean 'areas which are projected to remain climatically suitable for the given species up to at least 3.6°C global warming above pre-industrial levels, regardless of whether this is outside the species' current geographic range'. To assess the potential conservation value of these areas, an additional Zonation analysis was conducted for these species and their subspecies, extending the study area to include external climate refugia (Figure 5.2). In the case of subspecies, because climate refugia was identified at the species level, areas of external refugia were assigned to the geographically closest subspecies. All refugia-expanded study extents were carefully clipped to avoid overlap with the current geographic ranges of other giraffe species.

This dual-approach (i.e., within-range and extended-range analysis) allows for a comparative assessment of whether external climate refugia provide conservation value in terms of balancing climate suitability, resource availability, and threat levels. This is particularly relevant when evaluating future range dynamics or proactive management options, such as translocations.

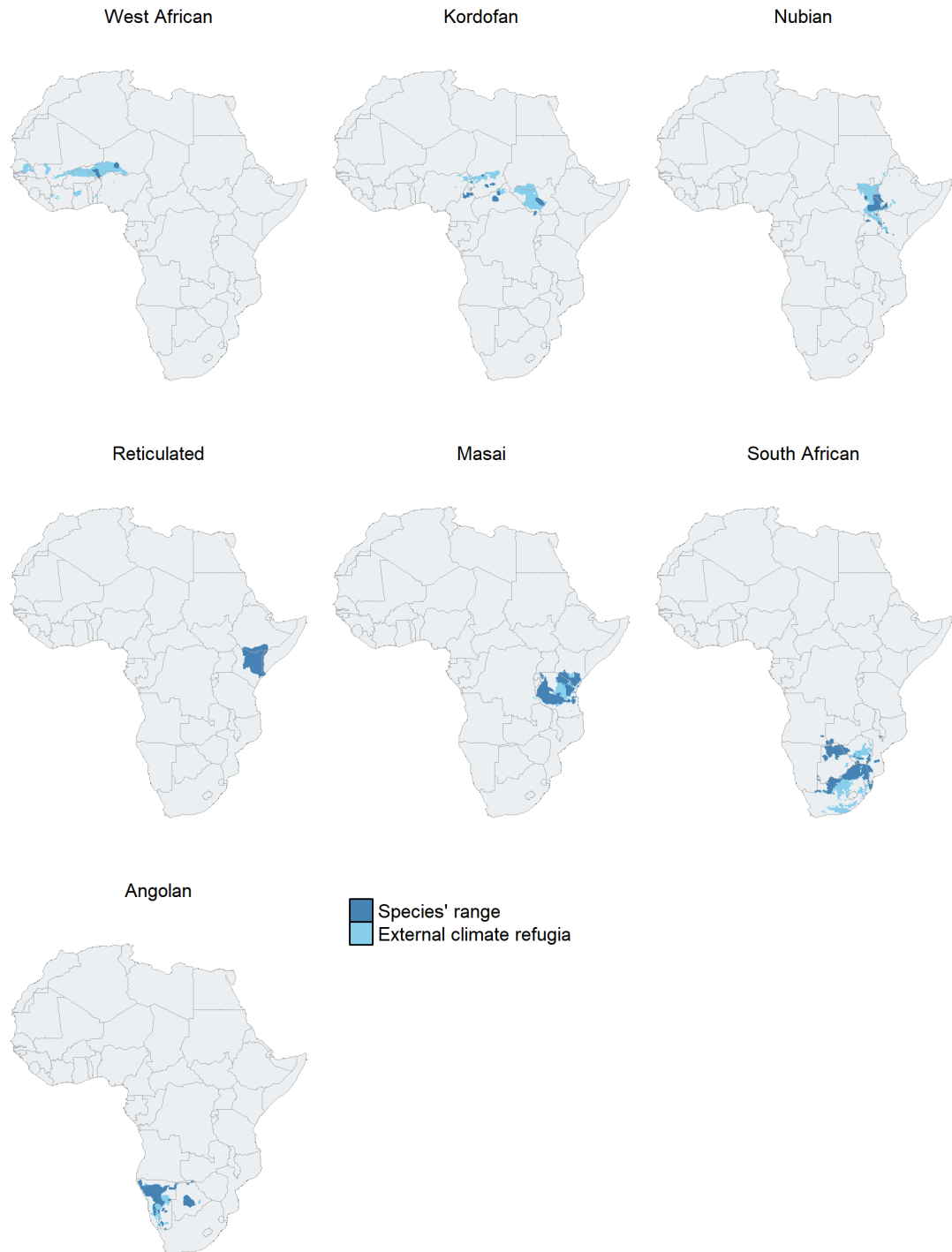


Figure 5.2: The study extents used in the Zonation analyses, with dark blue areas indicating the (sub)species' geographic range and the light blue areas showing external climate refugia used to define the extended study extent. Note that the Reticulated giraffe does not have any areas of external climate refugia, hence there are no light blue areas on this map. Climate refugia was assessed at the species level, and so for Northern giraffe (West African, Kordofan, and Nubian subspecies) and Southern giraffe (South African and Angolan subspecies), the climate refugia was designated to the geographically closest subspecies.

5.2.4 Climate scenarios

For this chapter, the term ‘scenarios’ refers to the distinct observed and projected climate conditions and associated timeframes used in the Zonation analyses. To match the global warming scenarios used to build the SDMs in Chapter 4, Zonation analyses were carried out for five different scenarios: Observed climate period, and increases of global annual mean surface air temperature of 1.5°C, 2°C, 2.7°C, and 3.6°C above preindustrial levels. The Zonation analyses were run for static global warming levels to show how priority areas may shift with increasing global warming. This gives conservation practitioners the flexibility to decide which warming level they would like to plan for, based on the most up-to-date information on projected global warming levels at the time of planning.

5.2.5 Feature inputs

Feature inputs for the Zonation analyses included the giraffe climate suitability layers from Chapter 4 and additional factors known to impact giraffe populations (discussed in Table 5.1). Each factor in the analysis represents a distinct pressure on giraffe populations; while some operate through related mechanisms (for example, different forms of habitat loss), they are incorporated as independent stressors that may occur simultaneously in a given area. Where multiple stressors coincide, this is reflected in a lower conservation priority ranking for those locations. This approach is directly relevant to conservation planning needs because identifying areas where several pressures coincide helps to highlight locations where giraffe are least likely to persist without substantial intervention, and, conversely, areas where fewer simultaneous constraints may offer better long-term conservation potential.

Feature inputs were the same for each (sub)species of giraffe, except for the giraffe climate suitability data, which was species-specific. All data were resampled, where applicable, to match the 10 arc minute resolution (~20 km at the equator) of the giraffe climate suitability data.

Table 5.1: Abiotic, biotic, and non-climatic anthropogenic impacts that can negatively affect giraffe populations. The feature dataset is the representative dataset for that feature used in the Zonation analyses, and where this dataset is from an outside source, the appropriate citation is given alongside it.

Category	Feature	Description of impact	Feature dataset
Biotic	<i>Food availability</i>	Food availability has been largely linked to giraffe population trends in some areas. In the Serengeti, large population growth in the past was attributed to an increase in resource availability, whilst poor nutrition from a lack of available forage was deemed one of the contributing factors for later population declines (Pellew, 1983; Strauss <i>et al.</i>, 2015). Giraffe diets can be largely varied, with some studies recording upwards of 30 plant species consumed (Leuthold and Leuthold, 1972; Innis, 1958). <i>Vachellia</i> and <i>Senegalia</i> species (previous, 'Acacia') make up a large proportion of their diet and are generally considered key forage species for giraffe (Dagg and Foster, 1976; Brenneman <i>et al.</i>, 2009; Mahenya <i>et al.</i>, 2016).	Binary climate suitability for each food species summed into two species richness layers: Acacia and non-Acacia.

Category	Feature	Description of impact	Feature dataset
	<i>Predation</i>	Lions (<i>Panthera leo</i>) are the main predator of giraffe, hunting both adults and calves, with calves being more vulnerable (Strauss and Packer, 2013). However, increases in lion abundance do not necessarily correlate with decreases in giraffe populations, with factors such as the abundance of other lion prey species potentially playing a role (Strauss and Packer, 2013; Strauss <i>et al.</i> , 2015). Nonetheless, the presence of predators in an area can affect giraffe habitat selection, sleep patterns, and vigilance behaviours (Cameron and du Toit, 2005; Périquet <i>et al.</i> , 2010; Thaker <i>et al.</i> , 2011; Burger <i>et al.</i> , 2020). Giraffe are particularly susceptible to attacks from predators whilst they are drinking, due to the body position they adopt by necessity (Périquet <i>et al.</i> , 2010).	Climate suitability for lions (<i>Panthera leo</i>)

Category	Feature	Description of impact	Feature dataset
Abiotic	<i>Drought</i>	Periods of drought have been documented to cause an increase in giraffe mortality (Mitchell <i>et al.</i> , 2010; Okello <i>et al.</i> , 2015). During the 2020-2023 Kenyan drought, 12 giraffe deaths were reported across Wajir, Ijara, and Tsavo West National Parks between February and October 2022 (Mwui <i>et al.</i> , 2022). Accounts of giraffe death from this drought vary, with one press release stating that 93 Masai giraffe died between June and November 2022 in Amboseli National Park alone (International Fund for Animal Welfare, 2023).	Maximum Consecutive months of severe drought (SPEI12 -1.5) (Price <i>et al.</i> , 2022)
	<i>Wet periods</i>	Research has shown that prolonged rainfall events can be correlated with giraffe mortality, possibly because of the higher associated parasite and disease abundance, and poorer quality nutrition in forage (Bond <i>et al.</i> , 2023).	Maximum Consecutive months of severe waterlogging (SPEI12 1.5) (Price <i>et al.</i> , 2022)

Category	Feature	Description of impact	Feature dataset
Non-climatic, anthropogenic	<i>Habitat loss</i>	Habitat loss impacts all giraffe species, and, for some populations, it has been deemed the greatest threat (Muller <i>et al.</i> , 2018; Gašparová <i>et al.</i> , 2020). Within giraffe ranges, habitat loss has been caused by conversion to agricultural land, deforestation, intense livestock grazing, and human population growth (Ciofolo, 1995; Suraud <i>et al.</i> , 2012; Ogutu <i>et al.</i> , 2014; Muller <i>et al.</i> , 2018). For Masai giraffe, population declines have been partly attributed to a loss of woodland habitat (Leuthold and Leuthold, 1978; Ottichilo <i>et al.</i> , 2000).	Global Human Modification Index (Kennedy <i>et al.</i> , 2020); Human population count (Gao, 2020)

Category	Feature	Description of impact	Feature dataset
	Poaching	Poaching occurs across all giraffe species' ranges (Dunn <i>et al.</i> , 2021); for three of the four species (Northern, Masai, and Reticulated), poaching has been responsible for population declines (Ciofolo, 1995; Suraud <i>et al.</i> , 2012; Ogutu <i>et al.</i> , 2014; Strauss <i>et al.</i> , 2015; Muller, 2018). Poaching often occurs in areas near human populations (Hofer <i>et al.</i> , 1996; Wato <i>et al.</i> , 2006; Marealle <i>et al.</i> , 2010), even near the borders and within protected areas. In the Serengeti, poaching on the border has been attributed as the prime cause of declining numbers of giraffe, and reports show between 3 and 200 giraffe are killed each year (Ogutu <i>et al.</i> , 2011; Strauss <i>et al.</i> , 2015).	Human population count (Gao, 2020)

The following sections describe each input dataset and any relevant methodology underlying the data.

Giraffe climate suitability

As a measure of the climate suitability for giraffe, SDM outputs from Chapter 4 were used in the Zonation analysis. The summed suitability outputs from each model and GCM combination were used to give a suitability scale of 0-88. This was preferable to using a binary transformed outputs or climate refugia layers as it allows for considerations of model agreement (both SDM and GCM). Whilst internal climate refugia is not used in this chapter, comparisons between refugia and Zonation outputs, where relevant, are made in Chapter 7 'Conservation Implications, Limitations, and Conclusions'.

Food availability

To include the potential impact of climate change-induced changes in food availability, SDMs generated by the Wallace Initiative (Warren *et al.*, 2018) were used in the Zonation analyses. The Wallace Initiative is a collaboration between researchers at James Cook University and the University of East Anglia to explore the impact of climate change on species. They have generated SDMs for ~135,000 terrestrial species, and the outputs have been used in multiple publications (for example: Warren *et al.*, 2013, 2018).

The Wallace Initiative SDMs were modelled using Maxent and eight bioclimatic variables: average maximum temperature of the warmest month of the year, average minimum temperature of the coldest month of the year, annual mean temperature, temperature seasonality, total annual rainfall, rainfall seasonality, rainfall of the wettest quarter, and rainfall of the driest quarter. The models generated by the Wallace Initiative used default Maxent settings, with the only difference being the generation of background points, which the Wallace Initiative generated separately (generating 10,000 points for each biome the species occur in). All models performed well, having an AUC of at least 0.7, and with less than 5% of models having a sensitivity or specificity value of less than 80% (Warren *et al.*, 2013, Supplementary Material).

To investigate the impact of climate change on giraffe food species, a list of plants found in giraffe diets was obtained from the literature (see Supplementary Material for a full list of

species names and references). Given the geographically distinct range areas of giraffe species, it was initially hoped that compilations of giraffe diet could be made species-specific. However, given that the literature is skewed towards Masai and Southern giraffe, this was not possible. As such, all plant species were compiled into one list, with the acknowledgement that giraffe diet may differ between species, but that species-specific differences in diet could be due to the presence or absence of plant species rather than species preference. In total, 116 plant species were identified. Due to changes in taxonomic nomenclature, a full review of species names was carried out, and several plants were removed from the list due to them being synonyms of accepted species names. There were only 20 plant species which had not been modelled by the Wallace Initiative and therefore were not included in this analysis. This left a total of 85 plant species, of which 20 were *Acacia* (*Senegalia* or *Vachellia* spp.).

To use the Wallace Initiative SDMs for each of the plant species in the Zonation analyses, they needed to be projected under the same climate data as the giraffe SDMs generated in Chapter 4. This was done by using the 'lambda' file produced in the original Maxent runs for each model. These lambda files are produced in all Maxent model outputs and contain information on the feature types used, regularisation parameters applied to the features, and the coefficients (lambdas) of the bioclimatic variables used in the equation to project climate suitability for the species. Input of these lambda files to a Maxent run alongside new climate data allows the original model to be projected to new data without additional training. For a given plant species, the lambda file was extracted from the Wallace Initiative model outputs, and Maxent was re-run with the default settings, the lambda file input, and the new climate data for the observed and projected warming (see Chapter 4 for climate data sources).

Each plant species was projected using the Maxent lambdas under the observed and projected climate, using 22 GCMs and global warming levels of 1.5, 2, 2.7, and 3.6°C. The output of each GCM projection was binary transformed using the 'maximum specificity and sensitivity threshold value' because the True Skill Statistic (TSS) was not available. This resulted in 22 binary outputs for each species and warming level, which were transformed into one singular output by applying a threshold, whereby a cell was deemed suitable if at least 15 of the 22 GCMs projected it as such.

The species layers were then grouped into ‘Acacia’ and ‘non-Acacia’ to represent the relative importance of Acacia species in the diet of giraffe. For both groups, the binary species layers were summed together, giving one raster for each scenario where the cell value corresponds to the number of species for which the climate is suitable. All species richness layers were capped at 15 to avoid a spatial skew generated by high species richness values. This value was chosen because a majority of a giraffe’s diet is often concentrated in fewer than 10 key species (Pellew, 1984; Furstenburg and van Hoven, 1994; Deacon and Smit, 2017; Deacon *et al.*, 2023).

Outputs of these species richness projections for the observed climate showed higher levels of species richness in southern and eastern Africa, coinciding with Masai, Reticulated, and Southern giraffe ranges (see Figure 5.3 and Figure 5.4). Under projections of global warming, outputs show lower levels of species richness across all areas, for both Acacia and non-Acacia plants. Across both observed and projected scenarios, species richness is lowest near areas of Northern giraffe geographic range, for Acacia and non-Acacia species.

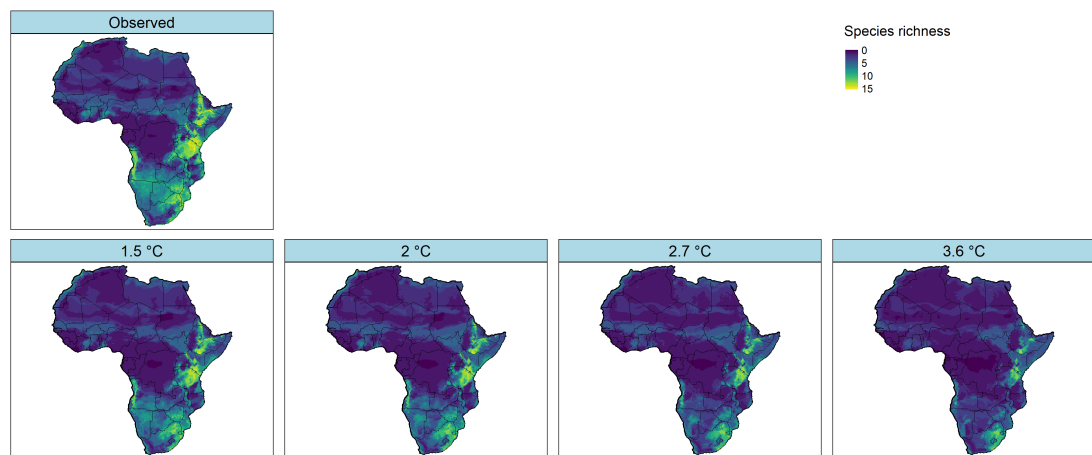


Figure 5.3: The observed and projected species richness of Acacia plants used in the Zonation analyses.

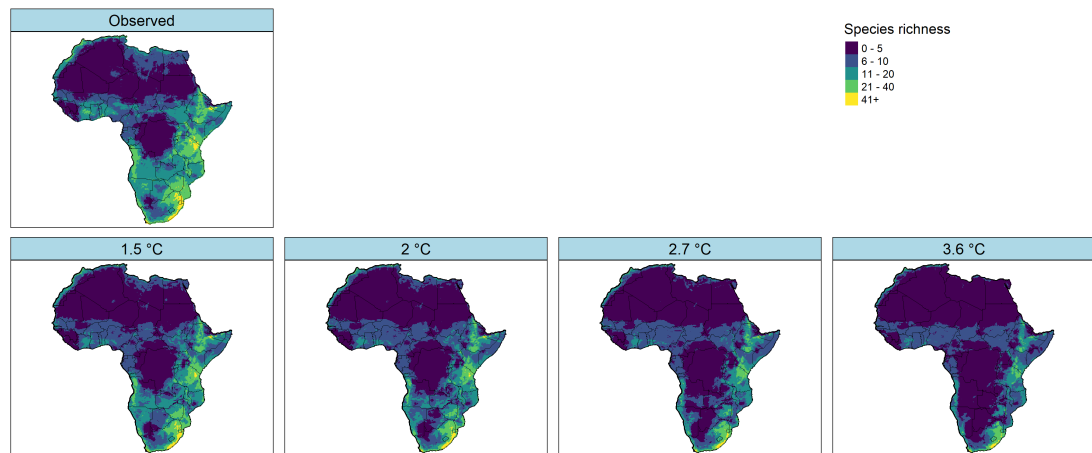


Figure 5.4: The observed and projected species richness of non-Acacia plants used in the Zonation analyses.

Predation

To incorporate the impact of predation, SDMs for lions (*Panthera leo*) were used as a proxy of predation pressure. Predation is an important factor to capture in the analysis because it is one of the main contributors to the high mortality rate of giraffe calves (see Chapter 2 ‘Literature Review’, section 2.3.6 ‘Predators’). As stress from climatic and non-climatic factors increases at higher levels of global warming, predation may become an increasingly important factor to consider for conservation. Because lions are a keystone species, it is acknowledged that they can also be a positive feature of a landscape, and as such, Zonation analyses excluding the predation layer were also run, and these are included in the Supplementary Material for this chapter. Additionally, as mentioned below in section 5.2.7, the ‘Ecological stability’ analyses use a positive weighting for *P. leo* climate suitability,

Whilst the Wallace Initiative had previously generated an SDM for lions, these models lacked enough occurrence data to construct a good fit for the entire expected lion range. Given the increase in publicly available occurrence data for lions over recent years, the decision was made to construct a new SDM for this species. Occurrence records were downloaded from GBIF using the filters ‘Occurrence Status: present’ and ‘Scientific name: *Panthera leo* (Linnaeus, 1758)’. This resulted in the download of 12,106 occurrence records (GBIF, 2024). These records were cleaned in R 4.2.2 (R Core Team, 2022) following the same procedure as for giraffe (see Chapter 4 Section 4.2.2 ‘Occurrence data’). Any occurrence points for the Asiatic lion subspecies were removed, maintaining only those for African lions. For ease of computation and to maintain consistency with the plant species models

used in the Zonation analysis, Maxent was run with default settings and the pseudo-absence points used in the original Wallace Initiative model.

The newly generated Maxent model for lions performed well, with a threshold-independent ROC value of 0.98. Each model output was binary transformed using the threshold with the highest TSS statistic, resulting in a TSS score of 0.86 and sensitivity and specificity values of 96.9 and 89.1, respectively. This resulted in one binary model for observed climate and 22 binary models for each of the projected climates (one per GCM). For each warming level, the 22 binary outputs were summed to generate a single layer representing the level of agreement among models on climate suitability for lions.

The model projections showed reduced areas of suitable climate for lions at higher levels of global warming (Figure 5.5). At 3.6°C of global warming, areas of suitable climate remain in southern Africa and parts of eastern Africa, but northern Africa becomes largely unsuitable.

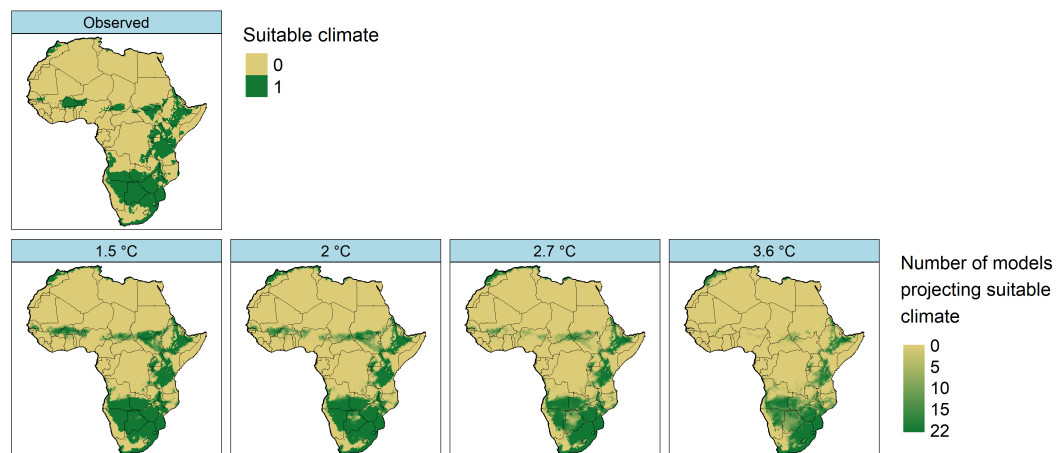


Figure 5.5: The observed and projected climate suitability for lions (*Panthera leo*). Green areas are suitable climate, and yellow areas are unsuitable.

Prolonged drought and waterlogging

To capture the impact of extreme, prolonged dry and wet conditions on giraffe, data for the 'Maximum Consecutive Months' (MCM) of SPEI12 -1.5 and 1.5 (severe drought and severe waterlogging, respectively) were used. SPEI12 is the 'Standardised Precipitation Evapotranspiration Index' calculated using the cumulative water balance over that month and the preceding 11 months, accounting for precipitation and evapotranspiration. SPEI was chosen as a metric of prolonged wet and dry periods instead of precipitation alone

because it represents a more ecologically relevant measure of available moisture for plants (Barnard *et al.*, 2021). By including both temperature and precipitation variables, it can capture patterns of drought which may not emerge from precipitation projections alone due to the interaction with temperature and subsequent water evaporation.

The SPEI -1.5 drought intensity was deemed an appropriate level of intensity because of the recorded giraffe mortality in Kenya in 2022 at this level (Figure 5.6). Drought data used is the same as that used in Chapter 3, originally from Price *et al.* (2022) - as such the methods to calculate the data are described in both these sources. The drought and waterlogging data used in Price *et al.* (2022) has a baseline period of 1961-1990 and is projected at 0.5°C increments, from 1.5°C to 4°C of global warming. To get data corresponding to the 2.7°C and 3.6°C of global warming used in this chapter, a simple linear interpolation was performed using data for 2.5°C and 3°C of global warming, and 3.5°C and 4°C of global warming, respectively. All SPEI12 data was originally at 0.5 degrees spatial resolution and was consequently resampled using a 'nearest neighbour' function.

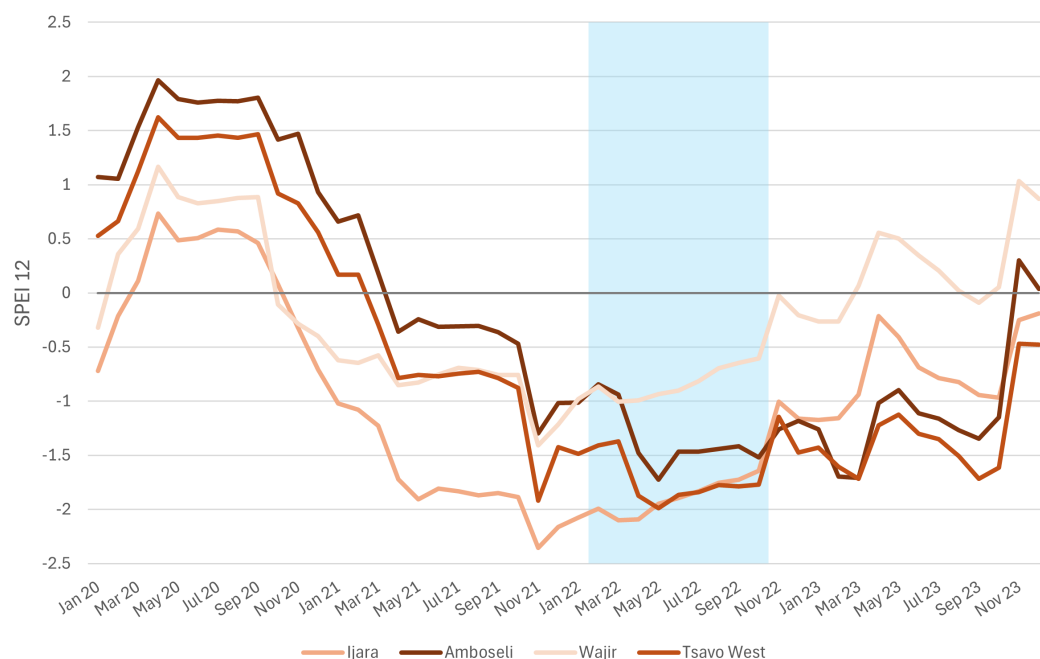


Figure 5.6: The SPEI12 value as an average over one degree resolution cells covering four areas in Kenya: Ijara, Amboseli National Park, Wajir, and Tsavo West National Park. The blue highlighted region shows the time period February 2022 – October 2022, when drought deaths were recorded in these regions. These SPEI12 values, obtained from the Global Drought Monitor (Beguería *et al.*, 2014), have been calibrated using the January 1950 to December 2010 baseline period, using the Thornwaite method for estimating potential evapotranspiration.

Habitat loss

To account for the impact of current land use on habitat suitability for giraffe, the Global Human Modification Index (gHM; Kennedy *et al.*, 2020) was used as a measure of habitat ‘intactness’. The gHM gives each cell a value from 0 to 1, representing the proportion of the cell which has been modified by humans (Figure 5.7).

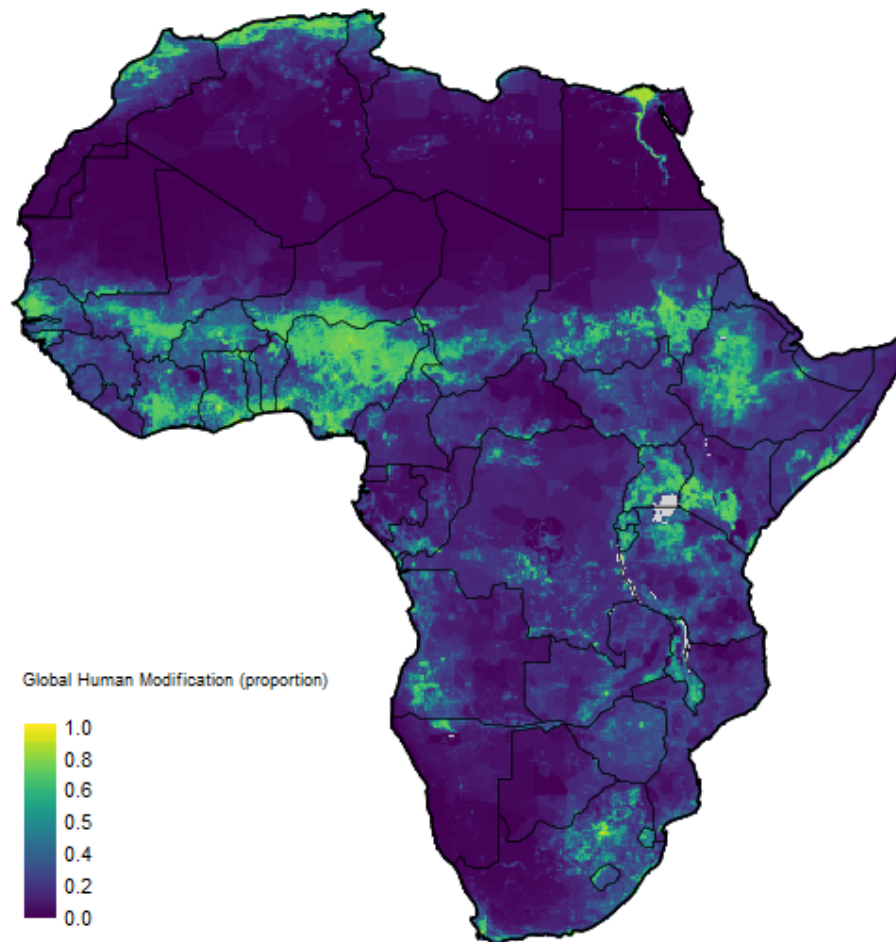


Figure 5.7: The global human modification (gHM) dataset used in the Zonation analyses. Higher values indicate a higher proportion of the cell has been modified by humans. Data from Kennedy *et al.* (2020).

Originally, layers accounting for percentage coverage and percentage increase in agriculture and urban areas were used, but the gHM layer was found to be more nuanced in accounting for additional anthropogenic factors and providing a good measure of the modification of the landscape. The gHM is computed through the input of 16 variables under the broader remit of five anthropogenic stressors – human settlement, agriculture, transportation, mining and energy production, and electrical infrastructure (see Table 5.2

for all input layers). Whilst not all of these variables may impact giraffe directly, previous research on Masai giraffe found gHM to be a core model predictor of habitat suitability (Muthiuru *et al.*, 2024). As such it was deemed appropriate for use in this Zonation analysis. The gHM layer has a median year of 2015 and is not available at any other time frames or projections. To match the spatial resolution used in the Zonation analyses, the gHM layer was resampled from 1 km² using the method 'average' so to maintain the proportional values.

Projections of Land Use and Land Cover (LULC) were deemed unusable for this analysis. This is because LULC are driven by anthropogenic and environmental factors, with complex feedback loops between the two which make it difficult to project without large uncertainties. Several datasets exist that project LULC under future scenarios (for example, Chen *et al.*, 2020; Hurtt *et al.*, 2020). Projections of land use in Africa show a general increase in cropland, grassland and urban land, but a decrease in forest land by 2100 (Yahaya *et al.*, 2024). These land-use projections can be informative but also remain highly uncertain due to the difficulty in projecting complex socio-economic factors, such as shifts in policy, agricultural practices, and afforestation or habitat restoration projects (Popp *et al.*, 2017; Albert *et al.*, 2020). Acknowledged limitations of these datasets also include coarse resolutions (Hurtt *et al.*, 2020); only accounting for the human elements driving land use change (Chen *et al.*, 2020); and not factoring in urban expansion or new settlements (Chen *et al.*, 2020). In the absence of reliable forecasts of LULC change, observed data on LULC can be used alongside projections of human population growth, which can act as a proxy for human-mediated landcover change.

Table 5.2: The input data used to construct the gHM layer (Kennedy *et al.*, 2020)

Stressor	Indicator
Human settlement	Human population density
	Built-up areas
Agriculture	Cropland
	Livestock
Transportation	Major roads
	Minor roads
	Two-tracks
	Railroads
Mining and energy production	Mining
	Oil wells
	Wind turbines
Electrical infrastructure	Powerlines
	Night-time lights

Given the link between human population density and the gHM layer, the feasibility of projecting gHM values using projections of human population density was explored. Because of the non-linear relationship between the two, and the large dataset size, a Big Additive Model (BAM) was used to project gHM. Whilst model summaries suggested a good ability to accurately project gHM, further investigation and model validation showed many unrealistic values in projections. These projections of gHM would also have been subject to the same uncertainties as projections of land use. Consequently, the decision was made to not to use projected gHM values, but to instead use projections of human population alongside the baseline gHM for future conservation planning.

Human population

Projections of human population were used as a proxy for associated anthropogenic impacts on species, for example, habitat loss or poaching. Projections of human population vary depending on the shared socioeconomic pathway (SSP) used; to investigate the impact of using different SSPs a sensitivity analysis was conducted. For this, the same Zonation analysis was run with each SSP, for each global warming level and species. The output of this showed no noticeable difference between priority maps

produced with each SSP – likely due to similar spatial patterns at the resolution used, and the weighting assigned to population layers. Following this, human population projections from SSP2 (Figure 5.8; Gao, 2020) were used because this SSP represents a ‘middle-of-the-road’ scenario of population growth, urbanisation, and spatial patterns of development (Jones and O’Neill, 2016). For each climate change scenario, population projections used in the Zonation analysis corresponded to the year which the climate projections are centred on. For example, for a scenario of 1.5°C global warming, the climate data is an average over the period 2021-2040, so the population count layer used for these Zonation analyses corresponds to the year 2030. All human population count layers were aggregated to the correct resolution in R, using the ‘sum’ function.

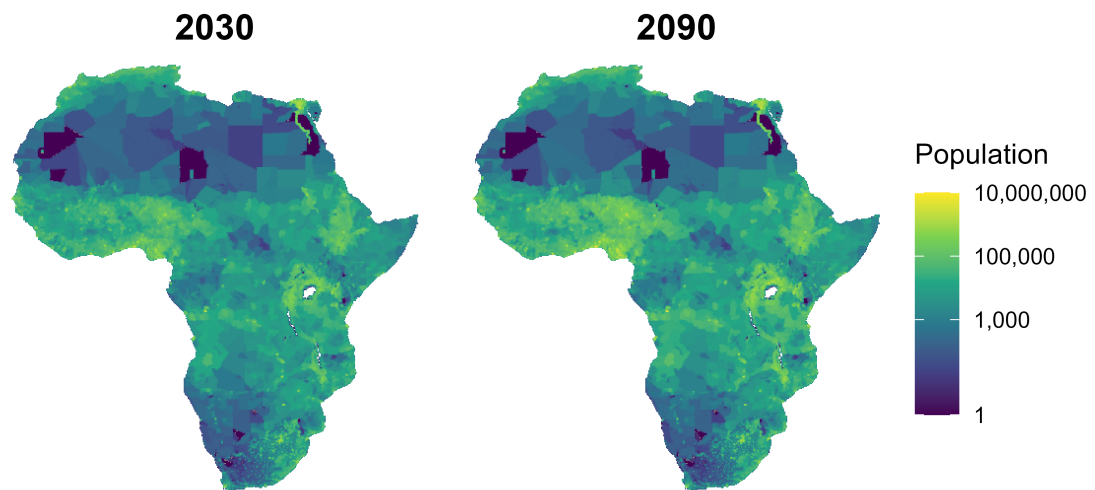


Figure 5.8: SSP2 human population projections for 2030 and 2090. Data displayed on a log10 scale, from dark blue-yellow (low-high). Data resampled to ~20 km resolution, from Gao (2020)

5.2.6 Zonation weightings

In Zonation software, each input feature can be assigned a weight to reflect the relative importance of that feature compared to others in the analysis. This weight can be either positive or negative to reflect desirable features or undesirable features that should be avoided. As such, in this analysis, giraffe climate suitability and both layers of food species richness were weighted positively, whilst lion climate suitability, gHM, human population

count, and maximum duration of severe drought and waterlogging were weighted negatively.

Zonation feature weights are decided by the user, meaning that there is an inherent element of subjectivity in the analysis, regardless of the knowledge that informs those decisions. To assess the impact of weight choices in the Zonation analysis, a Monte Carlo analysis was performed. The Monte Carlo analysis involves generating 1000 different feature weight combinations, running a Zonation analysis using each weight combination, and then calculating the variance in each grid cell across the 1000 Zonation runs. Cells with a higher variance are considered more susceptible to changes in prioritisation rank with different weightings. To perform this Monte Carlo analysis, each input feature was assigned a minimum and maximum weight bound from which to generate the random weighting (Table 5.3). These bounds were based on the upper and lower bounds of perceived relative importance of each layer to the survival of giraffe, using information from Table 5.1. The analysis was run using input variables for the observed period and 3.6°C of global warming, to see if the impact of feature weights was consistent across scenarios.

Table 5.3: The minimum and maximum weight bounds for each input feature, from which 1000 random weights were generated for the Monte Carlo analysis.

Feature layer	Minimum	Maximum
Giraffe Climate Suitability	1.25	2
Acacia food Species Richness	1	2
Non-Acacia food Species Richness	1	1.75
Lion Climate Suitability	-0.25	-1
Drought Duration	-0.5	-2
Waterlog Duration	-0.25	-2
Human Population	-0.5	-3
Human Modification Index (gHM)	-0.75	-3

The Monte Carlo analysis showed little impact of varying the weights within the prescribed bounds. The median variance in prioritisation ranks across all species was 0.005 and 0.003 for the observed and the future scenarios, respectively. Both scenarios had a 95th percentile value less than 0.05, at 0.045 for the observed and 0.048 for the future scenario. The full

outputs of this analysis are shown in the supplementary material. Given this, final weightings (see Table 5.4) were assigned to each feature based on the importance ascertained from Table 5.1. The weightings used in the Zonation analyses were kept constant across each species and scenario.

Table 5.4: Weightings used in the Zonation analysis for each species and scenario. ‘Feature value range’ shows the minimum and maximum possible values within a feature, for either the observed or projected Zonation runs. The gHM layer is continuous, and all others are discrete values.

Feature layer	Weight	Feature value range	
		Observed	Projected
Giraffe Climate Suitability	1.75	0-4	0-88
Acacia food Species Richness	1.5	0-15	0-15
Non-Acacia food Species Richness	1.25	0-15	0-15
Lion Climate Suitability	-0.25	0-1	0-22
Drought Duration	-1.0	0-360	0-360
Waterlog Duration	-0.75	0-360	0-360
Human Population	-1.25	0-Inf	0-Inf
Human Modification Index (gHM)	-2.0	0-1	NA

5.2.7 Ecological stability analysis

The core Zonation analyses are run at individual warming scenarios, so each priority ranking only accounts for the distribution of feature values in the given scenario. This means that the change in values is not accounted for, and thus the ecological stability of the area over time is not factored in. For example, given the cap in food plant species richness values of 15, a cell with an Acacia species richness value of 40 in the observed period and 20 in the 3.6°C scenario would rank the same as a cell with 20 in both scenarios. Whilst both cells may still be equally favourable to giraffe, one cell has had a drop in species richness of 50%. To address this issue and provide a complementary measure of priority rankings alongside the main Zonation analyses, an additional ecological stability Zonation analysis was conducted. This analysis gives a higher priority rank to cells which have remained the most stable from the observed period to 3.6°C of global warming. This analysis also works to further narrow down conservation priorities – where two cells may

have adjacent priority rankings in a Zonation run, it may be preferable to prioritise areas for conservation which are projected to remain the most stable under the highest warming scenarios.

The input layers for this analysis are described in Table 5.5, and values are based on the difference between values at the Observed reference period and 3.6°C global warming scenario. There are several key differences between how feature layers were treated in this analysis compared to the main Zonation analyses:

1. The absolute 'Lion climate suitability' layer is treated as a cost layer in the general Zonation analyses because of the threat of predation on giraffe. In the ecological stability analysis, however, the stability of lion climate suitability is treated as a positive feature to reflect the importance of lions as keystone species in an ecosystem.
2. The values for plant species richness were not capped to 15. In the general Zonation analysis, value capping meant that large species richness values would not skew priority areas. In the ecological stability analysis, values of food species richness loss were calculated against uncapped values to reflect actual change.
3. Dispersal for plants, lions, and giraffe was accounted for differently between the analyses. In the general Zonation analyses, unlimited dispersal was allowed in all climate suitability layers to allow for considerations of translocations and habitat restoration. In the ecological stability analysis, species climate suitability loss was calculated using a no dispersal scenario, meaning that each cell was only classed as suitable if it was also suitable in the previous warming scenarios and observed period.
4. An additional feature layer was added representing the proportion of total species richness remaining. This layer was an output from the Wallace Initiative, calculated over their diverse array of species distribution models (Warren *et al.*, 2018), including species of invertebrates, amphibians, plants, mammals, reptiles, and birds. It represents a measure of ecological stability as a whole, beyond simply the species which are most relevant to giraffe.

5. The gHM layer was not included in the ecological stability run due to the lack of projections available to calculate change. These outputs should therefore not be used to understand the suitability of an area for giraffe, only the extent to which areas are projected to be exposed to change under 3.6°C of global warming.
6. Feature inputs were given equal weightings of 'one' in the ecological stability Zonation runs, compared to the core Zonation analyses where features weights varied. Layer weightings were made equal so that the output represents ecological stability as a whole rather than favouring change in a specific feature.

To calculate changes in climate suitability for giraffe and lions, values at projections of 3.6°C and the observed period were standardised to a 0-1 score based on the possible maximum values. For giraffe, the values range from 0-4 in the observed period (agreement between four SDM algorithms) and 0-88 in the projected scenarios (combinations of four SDM algorithms and 22 GCMs). For lions, observed values were either 0 or 1, and projected values were between 0-22, because only a Maxent model was used with the 22 GCMs. Once these values had been standardised (by dividing by either 88 or 22 for giraffe and lions, respectively), the 3.6°C values were subtracted from the observed to show absolute loss of climate suitability, and then this value was subtracted from one to reverse the value and enable it to be used as a positive layer in the Zonation analysis (where a higher number is favourable).

Table 5.5: The input feature layers in the ecological stability analysis. CS is the 'climate suitability' for the given species

Input layer	Value	Weighting
Giraffe climate suitability	1 – (Observed CS – 3.6°C CS)	1.0
Lion climate suitability	1 – (Observed CS – 3.6°C CS)	1.0
Acacia species richness	Percentage remaining	1.0
Other food species richness	Percentage remaining	1.0
Human population count	Percentage change	-1.0
Maximum consecutive months of waterlogging	Percentage change	-1.0
Maximum consecutive months of drought	Percentage change	-1.0
Biodiversity Remaining	Proportion remaining	1.0

5.3 Results

The following sections show the Zonation priority rank outputs for each (sub)species. The outputs are shown in the order of: core Zonation runs within each (sub)species' geographic range, priority rankings against Protected Area (PA) status (UNEP-WCMC and IUCN, 2024), Zonation runs extended to areas of external climate refugia, and then the ecological stability Zonation runs. For Zonation runs across multiple scenarios, maps showing areas which rank consistently high (>0.9) or consistently low (<0.1) across all runs are included.

It is important to note that, whilst Zonation is a useful tool for identifying areas of highest relative conservation priority, it is not designed to attribute causation to individual drivers. Changes in priority ranking across warming levels reflect shifts in the relative balance between climate suitability, resource availability and threat layers, rather than the influence of one variable in isolation. Where desired, the mechanisms behind rank changes for a given site can be explored by inspecting the underlying input layers across scenarios. In this thesis, this is facilitated by the GiraffeClim application (Chapter 6), which allows direct comparison between Zonation outputs and individual layers such as drought, climate suitability, food plant richness and human modification. In this way, the method prioritises transparency and interpretability while retaining its primary purpose as a spatial decision-support tool rather than a mechanistic model.

5.3.1 West African giraffe (*Giraffa camelopardalis peralta*)

Core Zonation analysis

The Zonation outputs for the observed period show that the highest ranking areas are in the northern part of their western range area (Figure 5.9). Under higher global warming levels, this area loses priority rank and the highest ranking area becomes south of the western range portion. The priority ranking for the eastern portion of the range remains relatively stable under all global warming scenarios, gaining slight increases in priority in the northern portion of this range area. The only area which ranks in the top 10% across all scenarios is to the north of the western range area (Figure 5.9). Given that the West African giraffe's geographic range is small, this equates to $\sim 0.7\%$ of their total range area (342 km^2). A larger area (equating to 2.1% of their total range, and 1026 km^2) is ranked in the bottom 10% across all scenarios.

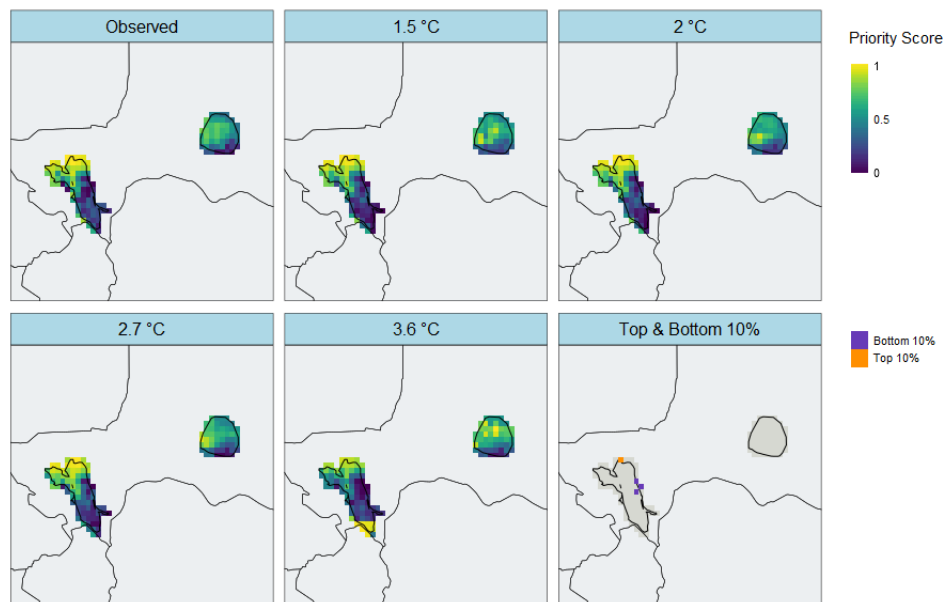


Figure 5.9: West African giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

Examining the PAs within the West African range shows that the Gadabédji Biosphere Reserve, designated by UNESCO in 2017 (previously a game reserve), decreases in average rank value across the warming levels (Table 5.6). Dosso, a partial fauna reserve, has a very low average rank across all warming levels, but does gain an increase in rank at 3.6°C. An examination of the input data shows that this increase in rank is driven by a decrease in Acacia and Non-Acacia species richness in the other areas of the subspecies' range, north of Dosso. Out of the 144 cells that make up the study area, a majority (129) are unprotected (Figure 5.10). As such, the priority rank values for unprotected cells spans the entire range of 0-1. The median rank value for the Government-Managed PA (GMPA) cells is less than 0.5 across all scenarios. Under 3.6°C of global warming, some of the protected cells have a large increase in priority rank, to more than 0.75.

Table 5.6: A selection of Protected Areas within the geographic range of West African giraffe, which are confirmed to have giraffe present, and the average Zonation value across the PA.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Gadabédji	UNESCO Biosphere Reserve	0.70	0.74	0.67	0.62	0.65	Niger
Dosso	Partial Fauna Reserve	0.25	0.15	0.16	0.16	0.51	Niger

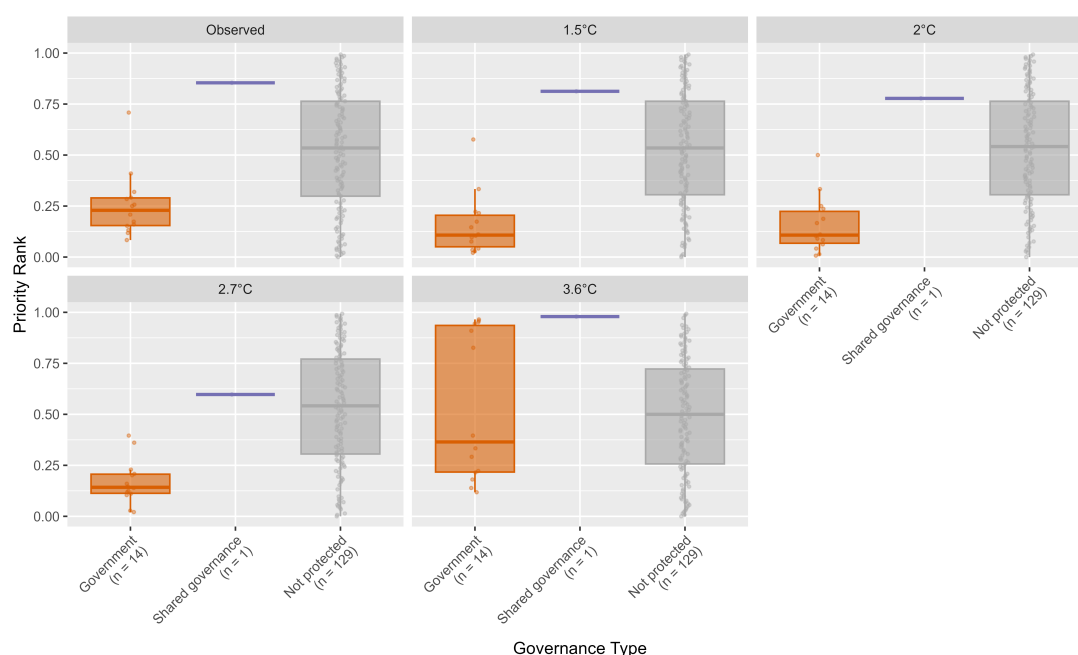


Figure 5.10: The priority rank for each cell in the West African giraffe core Zonation analysis, categorised by protected area designation and management type. Protected status is assigned to each cell based on the majority coverage of the cell, meaning that if a protected area only covers 25% of the cell and the rest is unprotected, it will be marked as unprotected. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas), and other.

Extended Zonation analysis

When the Zonation analysis is extended to include areas of external climate refugia, outside of the West African giraffe's current geographic range, Ghana, Benin, and Senegal contain areas of climate refugia that rank highly across all global warming levels (Figure 5.11). Across all global warming levels, the median Zonation rank outside of the West

African giraffe's range is higher than within their range. The median rank outside of the subspecies' geographic range varies between 0.51 - 0.52, across the scenarios, but within the range it varies from 0.46 - 0.39. In this extended Zonation run, the only areas which rank in the top 10% across all scenarios are outside of the current and historical geographic range, in Ghana.

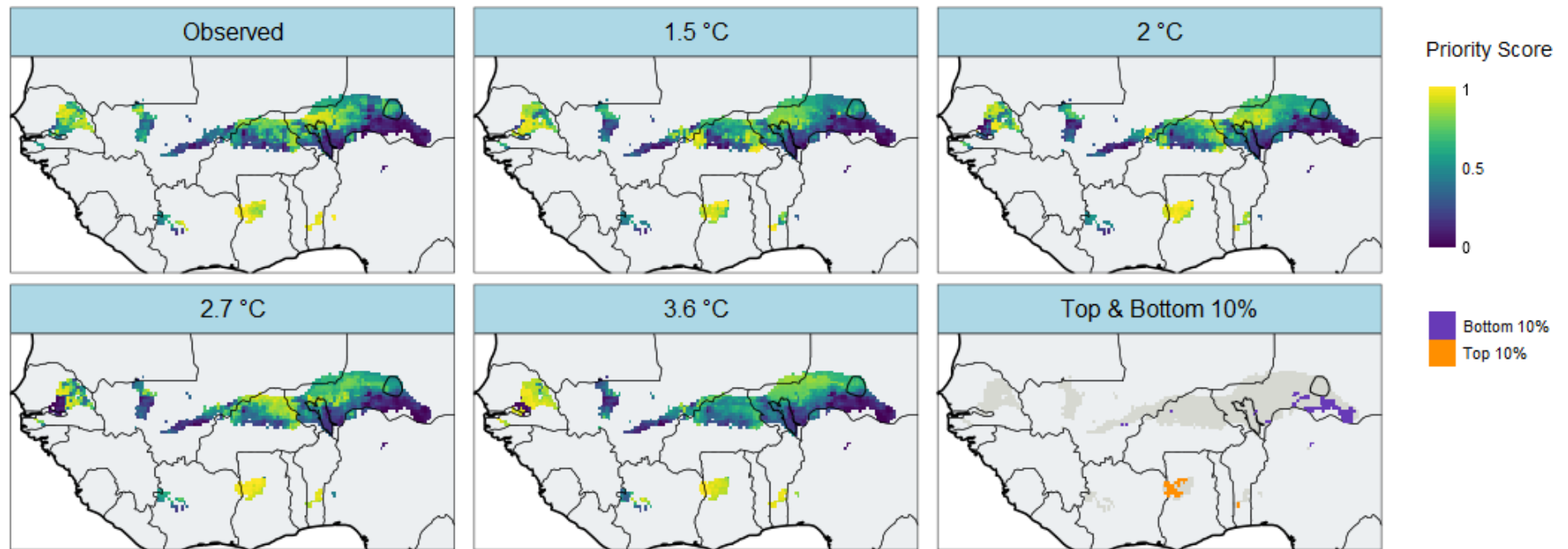


Figure 5.11: Zonation analysis outputs for West African giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the West African giraffe's geographic range and areas of external climate refugia for Northern giraffe (of which West African giraffe are a subspecies).

Ecological stability analysis

The ecological stability analysis shows that the areas which face the most change under 3.6°C of warming are the northern parts of both range polygons (Figure 5.12). The accompanying bivariate map highlights areas which are most ecologically stable up to 3.6°C but also ranked highly in the observed Zonation run. This shows that many of the most stable areas are those which are ranked low in the Observed Zonation run. The areas which are ranked high in both are to the western edge of the West African giraffe range.

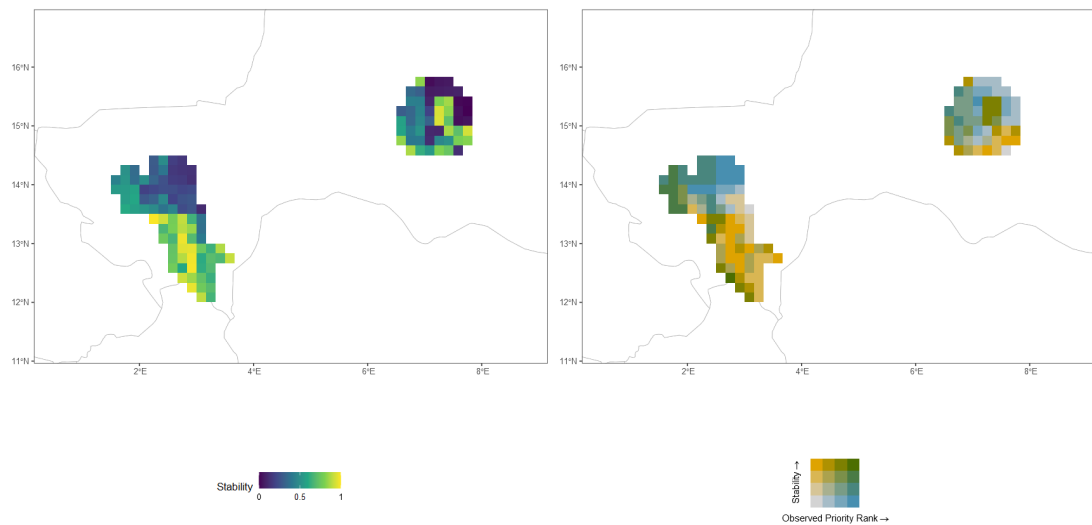


Figure 5.12: The ecological stability output for West African giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, the highest ranking priority areas for West African giraffe up to 2.7°C global warming are outside of PAs, in the northwest portion of the range. Both Gadabédji and Dosso are ranked below the top 25% and may need additional adaptation effort compared to other areas within the West African giraffe's geographic range to remain suitable for giraffe in the future. Some areas of external climate refugia have a high ranking, although the only area of external climate refugia which ranks consistently high across all scenarios is in Ghana – where giraffe have not historically existed. Generally, areas which have a high priority ranking in the core Zonation analysis have a lower stability ranking.

5.3.2 Kordofan giraffe (*Giraffa camelopardalis aniquorum*)

Core Zonation analysis

The areas with the highest priority rank within the Kordofan giraffe's range are the eastern and central portions, in South Sudan and the Central African Republic (Figure 5.13). Under higher global warming levels, the range in South Sudan retains the highest ranking. The priority ranking for the western portion of their range, in Chad and Cameroon, has the lowest rank across all warming levels. The only area within their current range which ranks in the top 10% across all scenarios is the Shambe National Park (NP) in South Sudan and equates to 2% (2395 km²) of their total geographic range (Figure 5.13). Areas ranking consistently in the bottom 10% are the most northwestern range areas, covering 10,952 km² and ~ 9.1% of the total range. Areas in the bottom 10% include Waza and Zakouma NP.

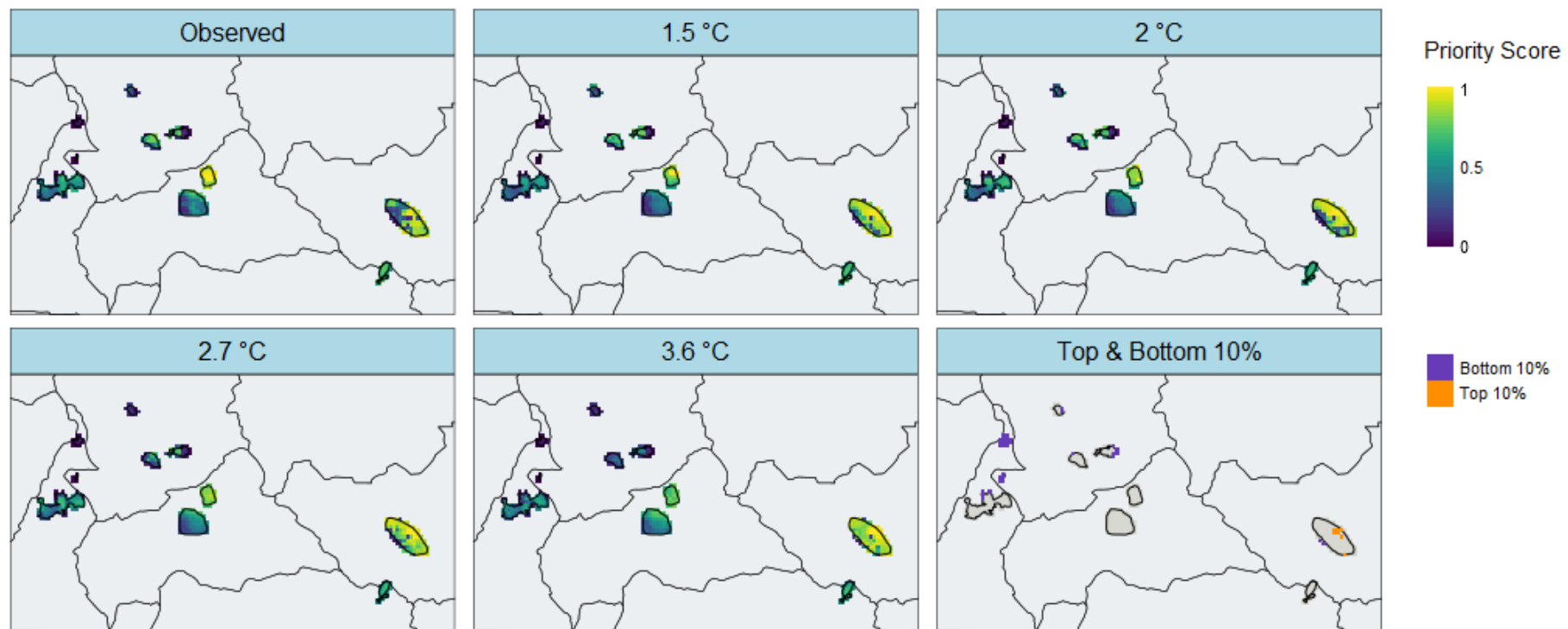


Figure 5.13: Kordofan giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

A selection of protected areas within the Kordofan giraffe's range that are confirmed to contain giraffe highlights a difference in the average priority rank of PAs (Table 5.7). As noted previously, Waza NP ranks in the bottom 10% across all warming levels, most likely due to the higher gHM values in this area relative to the rest of the range. Whilst some areas of Zakouma rank in the bottom 10% consistently, the average value is between 0.24 and 0.40 across all warming levels, and Garamba NP in the Democratic Republic of Congo has a priority rank of 0.58–0.68 across all runs. Shambe NP is ranked much higher, scoring a rank of at least 0.95 in all Zonation runs. This is likely due to the relatively high values for giraffe climate suitability, Acacia and non-Acacia species richness, and relatively low maximum duration of severe drought and waterlogging across all warming levels. Out of a total of 358 cells in the Kordofan giraffe's range, over half are unprotected, although the median priority rank is less than 0.5 for these cells (Figure 5.14). Around 14% of cells are Internationally-designated protected areas – these cells have a median priority ranking of over 0.6 and several have rankings more than 0.9. Priority ranks within Nationally-designated GMPAs vary with some cells at both extremes of the priority rank index.

Table 5.7: A selection of Protected Areas within the geographic range of Kordofan giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Waza	National Park	0.06	0.08	0.06	0.07	0.06	Cameroon
Shambe	National Park	0.95	0.98	0.99	0.99	0.99	South Sudan
Zakouma	National Park	0.38	0.40	0.38	0.37	0.24	Chad
Garamba	National Park	0.68	0.66	0.63	0.58	0.60	DRC

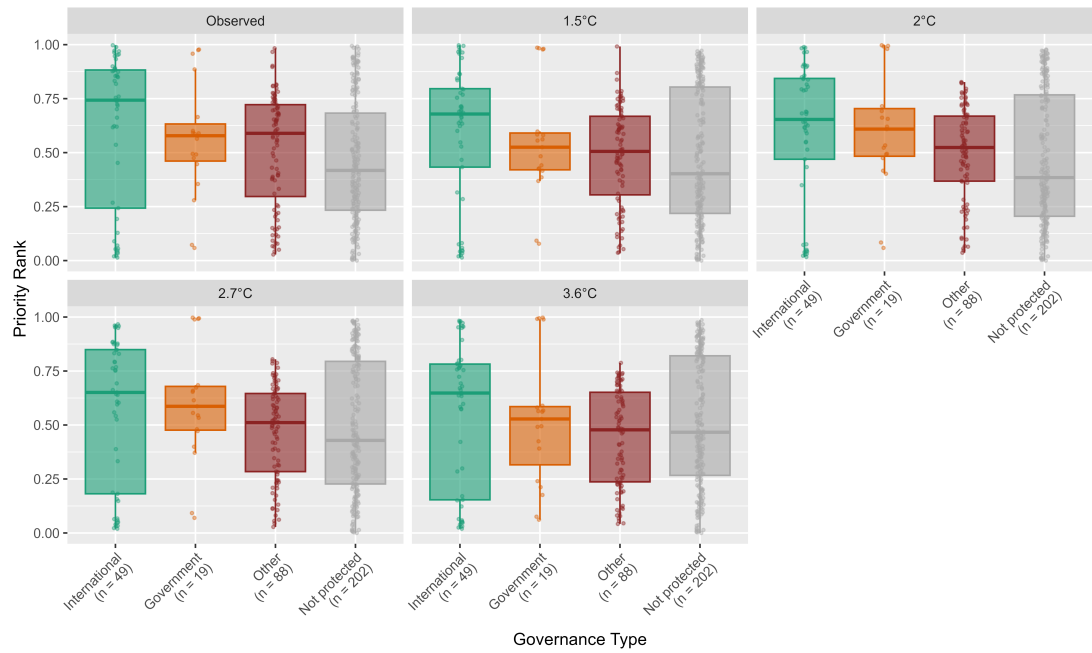


Figure 5.14: The priority rank for each cell ($n = 358$) in the Zonation analysis, organised by Protected Area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous people and/or local communities), and other.

Extended Zonation analysis

Extending the Zonation analysis to include areas of climate refugia shows broadly similar patterns to the range-constricted Zonation analysis – areas in South Sudan, near the Kordofan giraffe’s current range have the highest ranking (Figure 5.15). In the observed Zonation scenario, the median rank within the Kordofan giraffe’s current range is 0.61, compared to 0.47 in areas of climate refugia outside the current geographic range area. This pattern changes at different warming levels – at 1.5, 2, and 2.7°C, the median rank within the current range is between 0.44 - 0.49, and the median value outside the range is 0.52 - 0.54. At 3.6°C, the median rank values are the same within and outside of the range at 0.51. In this extended Zonation run, areas ranking consistently high and low follow the same pattern as the range-constricted Zonation run, with consistent top priority cells being found in South Sudan, and bottom 10% ranking cells to the west.

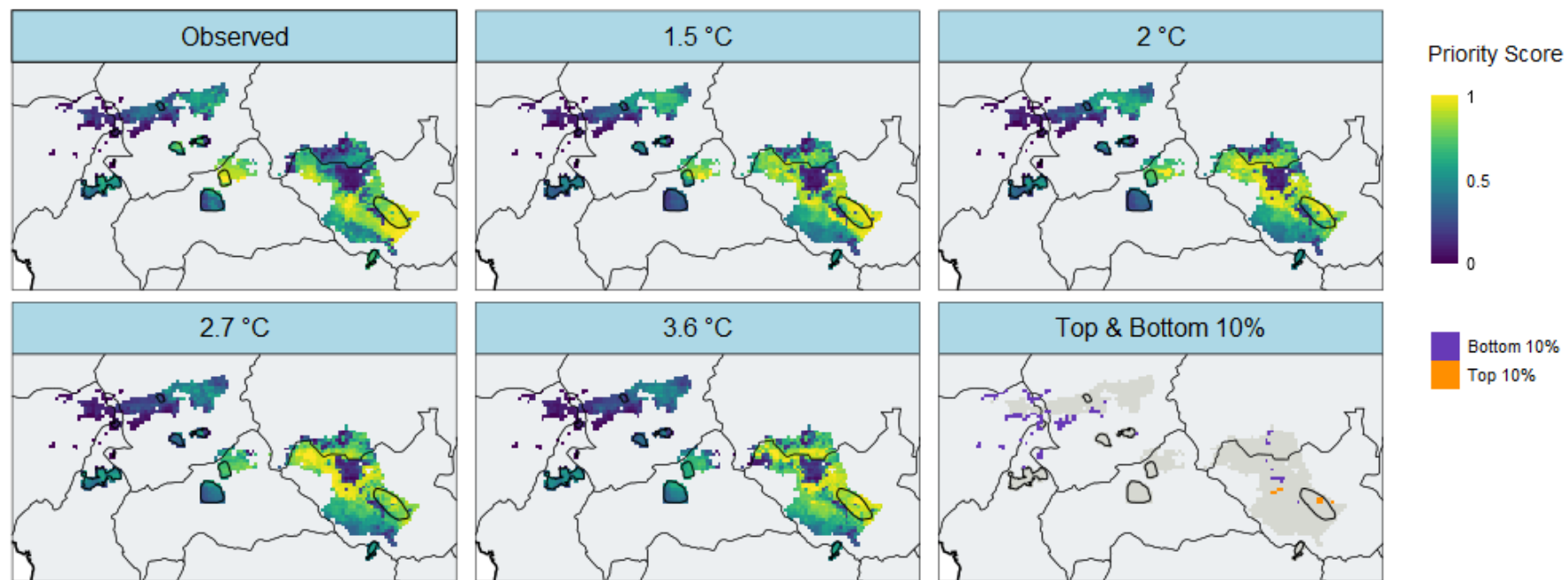


Figure 5.15: Zonation analysis outputs for Kordofan giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the Kordofan giraffe's geographic range and areas of external climate refugia for Northern giraffe (of which Kordofan giraffe are a subspecies).

Ecological stability analysis

The ecological stability analysis shows some similar spatial patterns to the core Zonation analysis, with areas to the north part of the range being ranked poorly (Figure 5.16). Combining the ecological stability outputs with the observed priority ranks shows several areas which rank high in both: the northernmost range in the Central African Republic, and several cells in the South Sudan range.

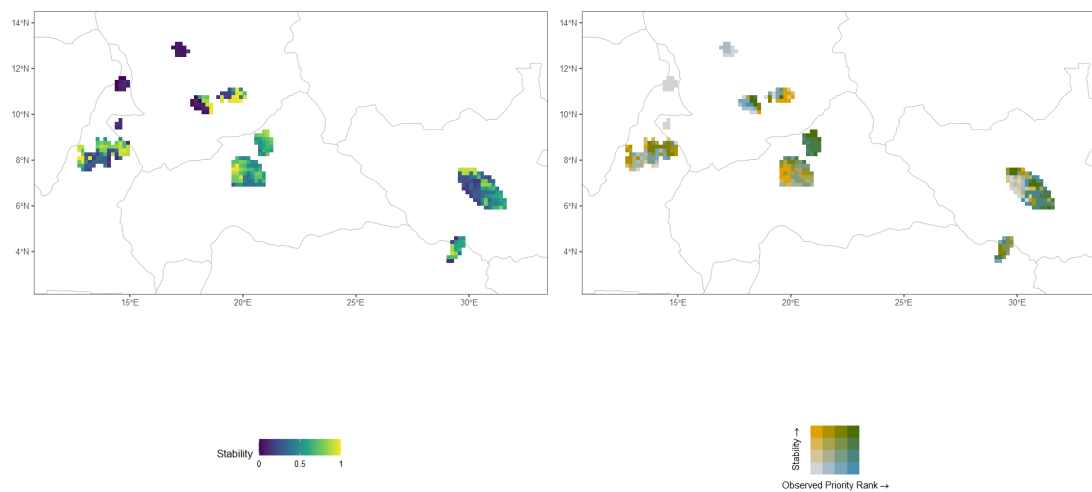


Figure 5.16: The ecological stability output for Kordofan giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right) for Kordofan giraffe

In summary, the Kordofan giraffe's current range area within South Sudan is a key priority area, being ranked in the top 10% across all warming levels. Cameroon and Chad Kordofan giraffe range areas are ranked consistently low and may need additional adaptation effort to remain suitable for Kordofan giraffe under global warming. Shambe NP is a key conservation priority for giraffe and may be able to support giraffe populations with less adaptation effort than other areas. Even when the Zonation analysis is extended to external climate refugia, Shambe NP ranks consistently high. Stability outputs show this area along with the northernmost range in the Central African Republic are the most stable areas under the highest level of warming.

5.3.3 Nubian giraffe (*Giraffa camelopardalis camelopardalis*)

Core Zonation analysis

The highest ranking area within the Nubian giraffe's range is in South Sudan and Uganda in all Zonation scenarios (Figure 5.17). The fragmented range area within Kenya ranks poorly at all warming level scenarios. The map showing areas which rank consistently high and low reiterates this – the 1.6% (2395 km²) of the Nubian giraffe's geographic range which ranks consistently in the top 10% is in the Kidepo Valley NP in Uganda, whilst the areas of consistent bottom 10% ranking are largely found in the fragmented range in Kenya.

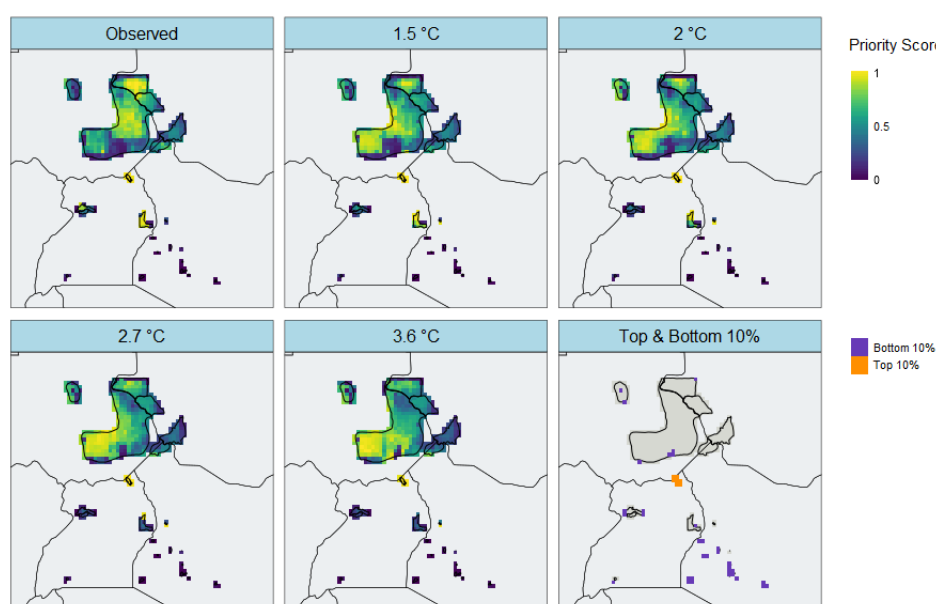


Figure 5.17: Nubian giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

Several PAs within the Nubian giraffe's range that are confirmed to contain giraffe have an average rank below 0.5 in all Zonation runs, whilst Kidepo Valley NP in Uganda is ranked at least 0.98 in all Zonation runs (Table 5.8). Boma NP in South Sudan, and Pian Upe in Uganda show sharp declines in priority rank from the observed run to higher levels of global warming. An examination of the input layers indicates that the decline in Pian Upe is primarily associated with projected losses of both Acacia and non-Acacia browse species richness, which remain comparatively higher across much of the remaining range. Climate suitability for Northern giraffe in Pian Upe declines only slightly relative to other areas, and the projected duration of severe drought is similar. A similar pattern is found in Boma NP,

where browse species richness is projected to decline more rapidly than in neighbouring range areas, accompanied by an increase in the maximum number of consecutive months of drought, even at lower warming levels. Just over half of the cells (51%) in the Nubian giraffe's range are protected (Figure 5.18). The vast majority of these cells are in Nationally designated, government-managed PAs and these cells are some of the top ranking cells at all warming levels. At higher levels of global warming, more of the unprotected cells rank highly.

Table 5.8: A selection of Protected Areas within the geographic range of Nubian giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Murchison Falls	National Park	0.41	0.31	0.24	0.20	0.19	Uganda
Kidepo Valley	National Park	0.98	0.99	1.00	1.00	0.98	Uganda
Boma	National Park	0.78	0.66	0.65	0.59	0.55	South Sudan
Pian Upe	Wildlife Reserve	0.83	0.82	0.60	0.36	0.24	Uganda
Omo	National Park	0.40	0.41	0.39	0.34	0.29	Ethiopia

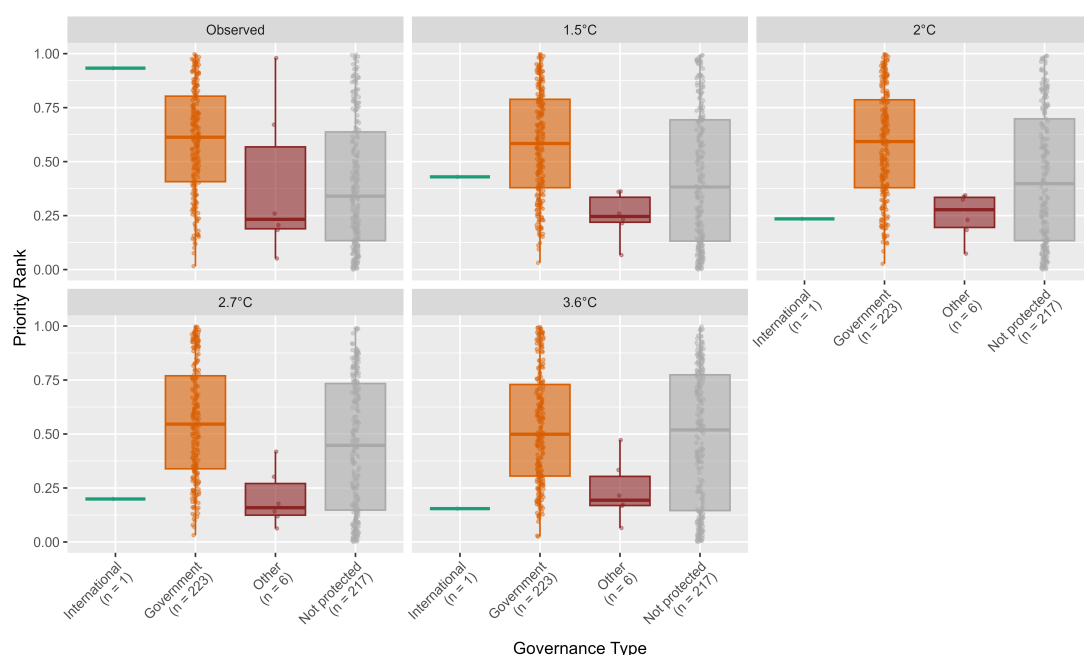


Figure 5.18: The priority rank for each cell ($n = 447$) in the Zonation analysis, organised by Protected area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas).

Extended Zonation analysis

When the Zonation is extended to include areas of external climate refugia, an area in the northeast of Uganda is the highest ranking across all scenarios (Figure 5.19). The large range area within South Sudan still ranks highly compared to the fragmented range in Kenya. Median rank values show a large difference between values within Nubian giraffe's current range and outside of this range in areas of climate refugia. In the Observed period, there is a median rank of 0.75 within the range, and 0.37 outside of the range. This pattern continues across all warming scenarios, and at 3.6°C the median rank is 0.65 within the range and 0.42 outside. Even when the Zonation analyses are extended to include climate refugia, the range in Kidepo valley ranks in the top 10% across all scenarios.

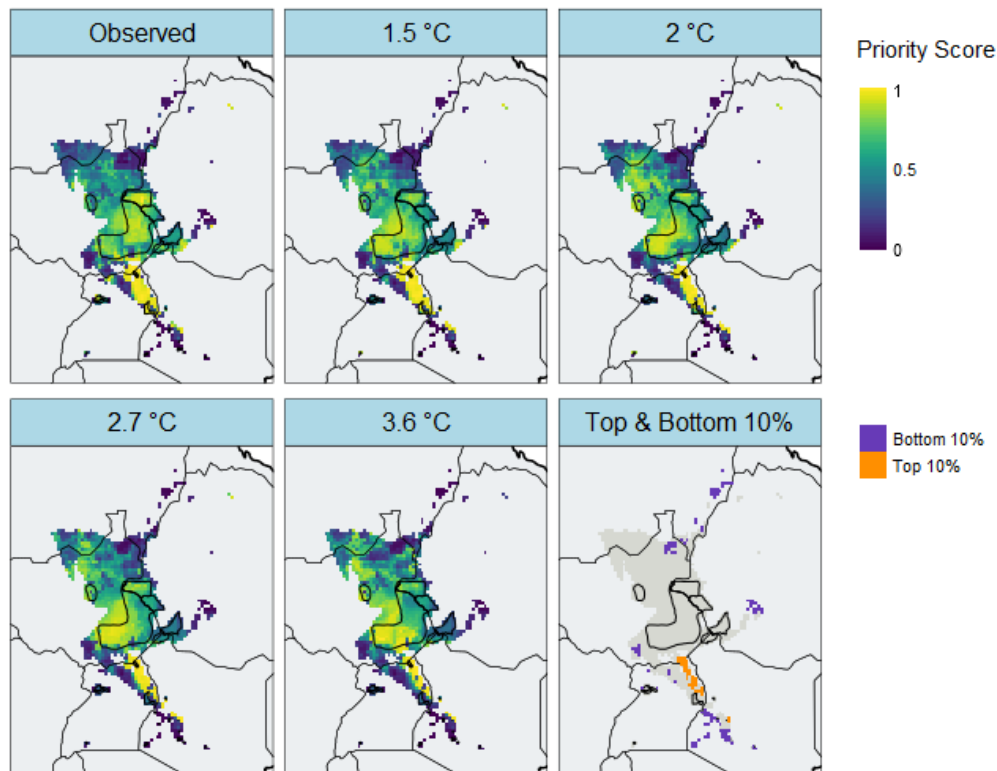


Figure 5.19: Zonation analysis outputs for Nubian giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the Nubian giraffe's geographic range and areas of external climate refugia for Northern giraffe (of which Nubian giraffe are a subspecies)

Ecological stability analysis

The ecological stability analysis shows Kidepo Valley, some fragmented areas in Kenya, and southern South Sudan ranking highly (Figure 5.20). Kidepo Valley is the only area which ranks highest in stability as well as the observed priority ranking. Many of the areas in Kenya and South Sudan rank high in stability but very low in Observed priority rank.

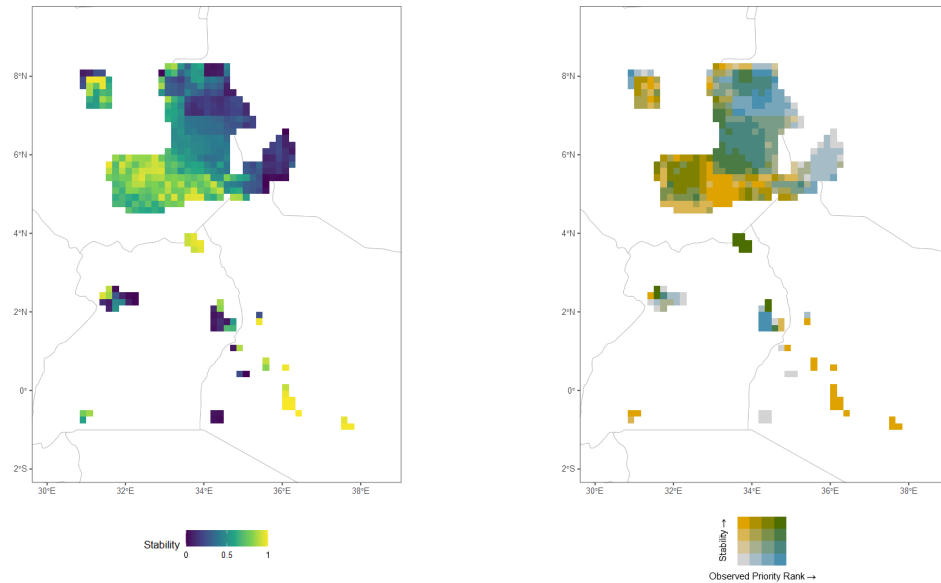


Figure 5.20: The ecological stability output for Nubian giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, Kidepo valley in Uganda is a key conservation priority area for Nubian giraffe. It ranks consistently in the top 10% across warming levels and has a high level of stability compared to other areas within the geographic range. Areas of external climate refugia adjacent to Kidepo valley also rank highly and could be good candidates for translocations if needed. Murchison Falls NP in Uganda ranks poorly across all warming levels and may therefore need higher adaptation effort to support giraffe populations in the future.

5.3.4 Reticulated giraffe (*Giraffa reticulata*)

Core Zonation analysis

Within the Reticulated giraffe's range, the highest ranking areas across all scenarios are in central Kenya and southern Ethiopia (Figure 5.21). The eastern portion of the Reticulated range ranks consistently low, and the area to the south-west of the range ranks lower at higher levels of global warming. It should be noted that some areas in the south-western portion of the range rank higher in Zonation analyses which exclude predation as a negative feature layer (see Figure S5.2 in supplementary material). Several cells in southern Ethiopia and central Kenya rank consistently in the top 10% across all Zonation runs. These areas are 2.4% (9240 km²) of the total geographic range of Reticulated giraffe. Cells ranking consistently in the bottom 10% are found in eastern and central Kenya, and account for 5.8% (22,246 km²) of the Reticulated giraffe's range. Because areas of climate

refugia for Reticulated giraffe do not extend beyond their current geographic range, no additional Zonation analyses were run for external climate refugia.

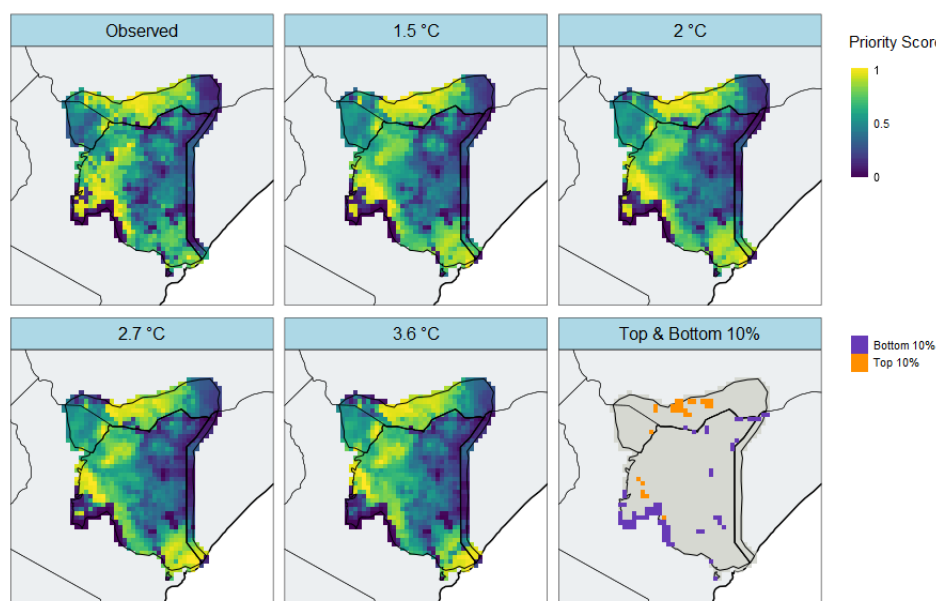


Figure 5.21: Reticulated giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

Several PAs with confirmed Reticulated giraffe presence rank very highly in the observed Zonation run, up to 3.6°C warming (Table 5.9). The Laikipia National Reserve in Kenya loses average rank value across global warming levels, from 0.68 in the Observed Zonation run, to 0.11 at 3.6°C warming. The input data layers show that the food species richness in this area is projected to remain high, but that climatic suitability for giraffe is projected to decline more than in other parts of the range, and human population density is projected to become comparatively higher, potentially contributing to the reduction in rank. The Rahole National Reserve gains rank at higher warming levels, but only ranks at 0.44 in the observed period. This PA illustrates a case where rank change is likely driven primarily by relative changes elsewhere rather than substantial changes within the PA itself. Underlying input data remains broadly consistent across warming levels in Rahole (apart from a small increase in the maximum duration of severe drought from 9 to 14 months across scenarios), whereas other areas – particularly those in the northern portion of the Reticulated giraffe's range – are projected to experience larger declines in climatic suitability and browse species richness. In addition, Rahole has a relatively low gHm value compared to many other areas in the range. There are 1,122 cells in the Reticulated giraffe's

geographic range, and 867 of these are unprotected (Figure 5.22). Around 15% of the cells are Nationally designated, government-manged PAs, which have a high median rank across all Zonation runs of at least 0.75. Indigenous or Community managed areas tend to have a high median rank, fluctuating around 0.75 across all warming levels, and many of these cells rank in the top 10%.

Table 5.9: A selection of Protected Areas within the geographic range of Reticulated giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Rahole	National Reserve	0.44	0.42	0.45	0.51	0.59	Kenya
Laikipia	National Reserve	0.68	0.36	0.35	0.09	0.11	Kenya
Sera	Community Conservancy	0.94	0.97	0.94	0.85	0.79	Kenya
Melako	Community Conservancy	0.82	0.73	0.68	0.65	0.69	Kenya
Shura	Community Conservancy	0.78	0.64	0.62	0.63	0.68	Kenya

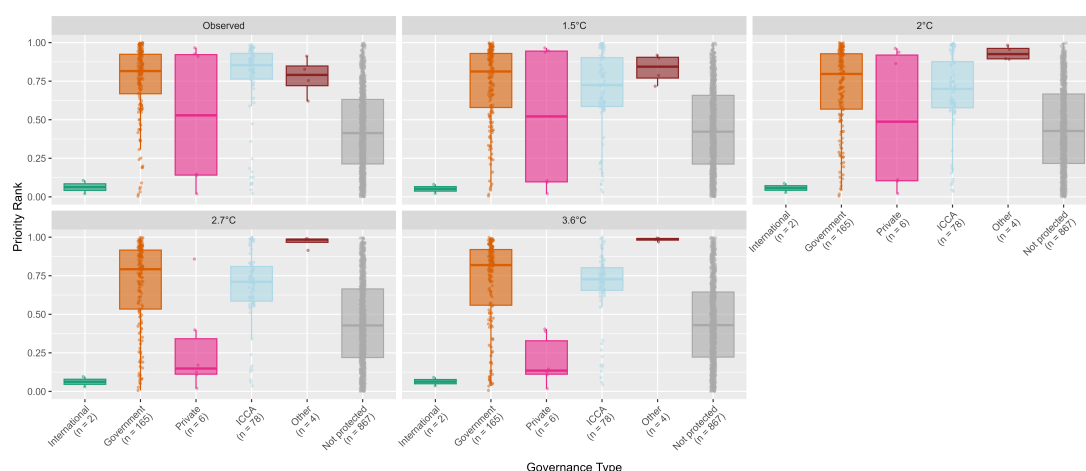


Figure 5.22: The priority rank for each cell ($n = 1,122$) in the Zonation analysis, organised by Protected area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas).

Ecological stability analysis

The ecological stability Zonation run highlights areas to the west of the Reticulated giraffe's range as most stable (Figure 5.23). The bivariate map shows many areas rank highly in either the ecological stability run or the Observed priority rank, but few areas rank highly in both. Areas that do rank highly in both are found predominantly towards the edges of the range.

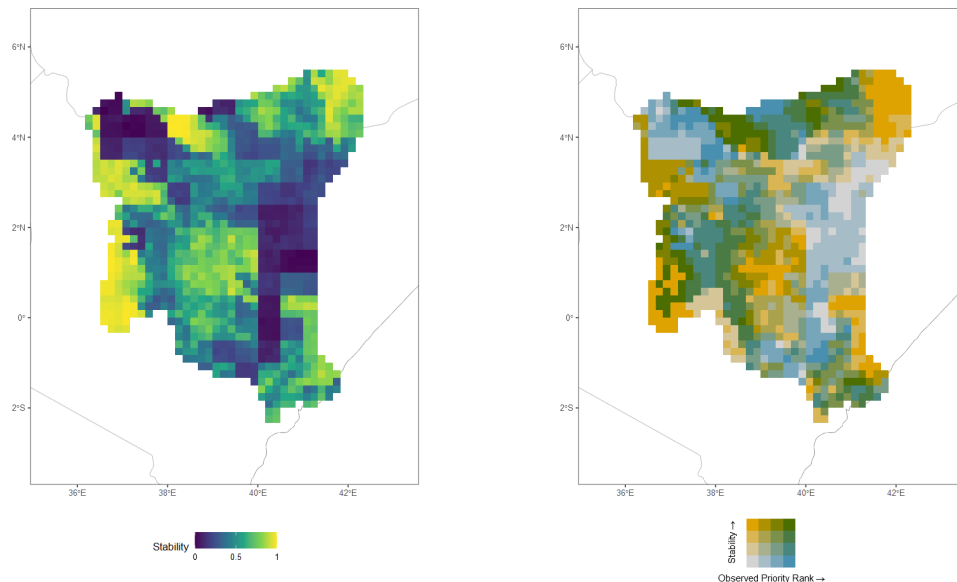


Figure 5.23: The ecological stability output for Reticulated giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, western and northern portions of the Reticulated giraffe's range have the highest priority rankings across all warming levels. At higher warming levels, the southwest portion of the range decreases in priority rank and may need higher adaptation effort to support giraffe populations under climate change. Sera Community Conservancy maintains a high priority rank until 2.7°C, and at all levels of warming some of the top ranking cells are found in Government-managed PAs.

5.3.5 Masai giraffe (*Giraffa tippelskirchi tippelskirchi*)

Core Zonation analysis

For Masai giraffe, the highest ranking range areas are near the border of Kenya and Tanzania (Figure 5.24). This is true under all Zonation scenarios, highlighted by the map showing areas in the top 10% ranking across all scenarios. These areas of consistent priority constitute 2% (9,925 km²) of Masai giraffe range. As global warming increases, the

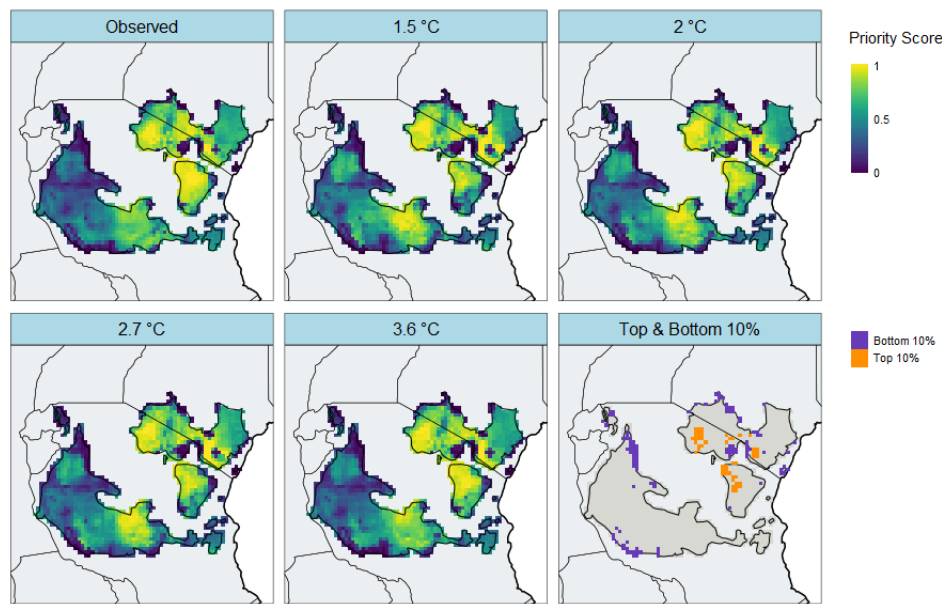


Figure 5.24: Masai giraffe giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

western part of the Masai giraffe's range becomes less highly ranked. A much larger area of 6.8% of the Masai giraffe's range (34,567 km²) ranks consistently in the bottom 10%. For Masai giraffe, all areas of consistent priority are to the northeastern portion of their range area, near the Tanzania-Kenyan border. The Tsavo West NP in Kenya has large portions which are ranked in the top 10% across all global warming levels, alongside the Serengeti NP and Ngorongoro Conservation Area in Tanzania.

Out of the selected PAs examined in Table 5.10, only Tsavo West and Serengeti NP have an average rank above 0.75 under 3.6°C global warming. Tsavo East has the highest rank of the PAs in the Observed Zonation run, but has a lower rank at increasing warming levels and is only ranked at 0.64 at 3.6°C global warming. This decline is likely driven by a strong reduction in projected climatic suitability for Masai giraffe, alongside a projected increase in the maximum duration of severe drought. In contrast, Tsavo West retains high climate suitability for Masai giraffe and consistently high Acacia species richness across all warming levels, which likely explains its persistently high rank. Over half of the cells in the Masai giraffe's range are either Nationally- or Internationally-designated PAs (Figure 5.25). Of the nationally designated PAs, the majority are GMPAs equating to ~40% of the Masai giraffe's range. These GMPAs span a large range of priority rankings, but the median rank is ~0.62–0.7 across all Zonation runs. The median rank in cells with internationally designated PA

status is relatively high in the Observed Zonation run (~0.7), but falls at higher warming levels, with a median rank below 0.25 at 3.6°C. Only 29 cells are ICCAs (Indigenous and Community Conserved Areas), but in each Zonation run some of these cells are top ranking. The median Zonation rank in unprotected areas is less than 0.5 across all scenarios, showing that over the entire study extent, PAs have a higher median rank.

Table 5.10: A selection of Protected Areas within the geographic range of Masai giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Tsavo East	National Park	0.97	0.81	0.73	0.66	0.64	Kenya
Tsavo West	National Park	0.94	0.96	0.95	0.92	0.86	Kenya
Akagera	National Park	0.30	0.41	0.45	0.42	0.39	Rwanda
Serengeti	National Park	0.81	0.85	0.85	0.82	0.76	Tanzania
Ruaha	National Park	0.76	0.69	0.67	0.68	0.65	Tanzania
Katavi	National Park	0.65	0.39	0.31	0.33	0.40	Tanzania

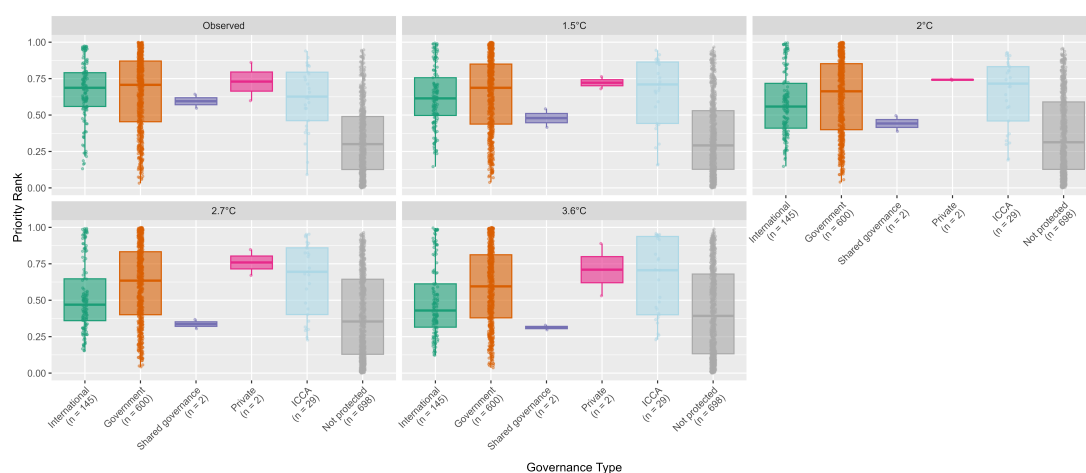


Figure 5.25: The priority rank for each cell ($n = 1,476$) in the Zonation analysis, organised by Protected area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas).

Extended Zonation analysis

Extending the Zonation analysis outside of the range to capture areas of climate refugia shows some additional areas in central Tanzania which rank highly across multiple warming levels (Figure 5.26). Despite this, all cells which rank in the top 10% across all warming levels are still within the Masai giraffe's range. When comparing median rank values for the observed period, areas outside of the species' range have a lower value than those inside the range, at 0.3 and 0.59 respectively. This changes at higher warming scenarios and by 3.6°C of warming, the median rank value is higher in areas of climate refugia outside of the species range than within, at 0.58 and 0.51 respectively.

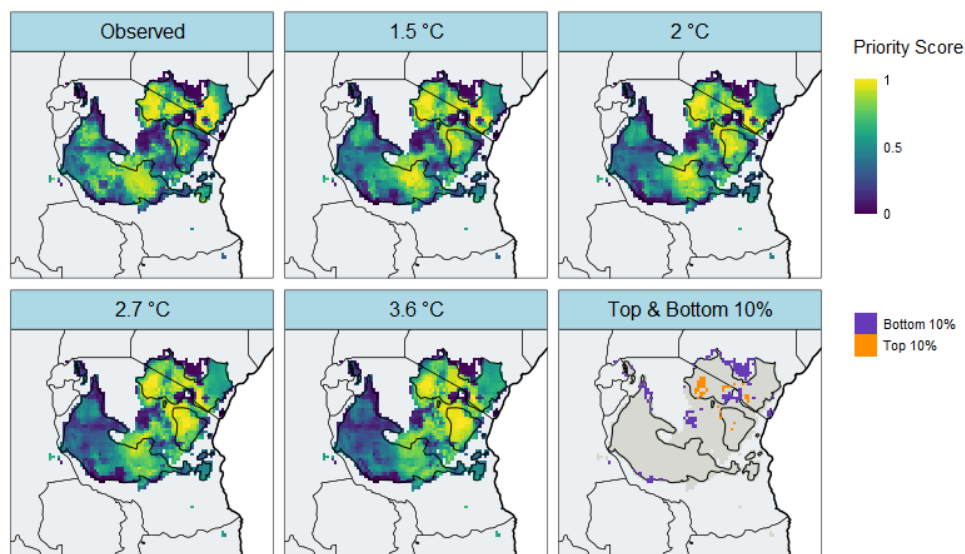


Figure 5.26: Zonation analysis outputs for Masai giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the geographic range and areas of external climate refugia for Masai giraffe

Ecological stability analysis

Examining areas of ecological stability highlights the central range portion in northeast Tanzania as the most stable up to 3.6°C warming (Figure 5.27). Several areas on the Kenya-Tanzania border rank highly in the Observed priority ranking but have some of the lowest ecological stability of the entire range.

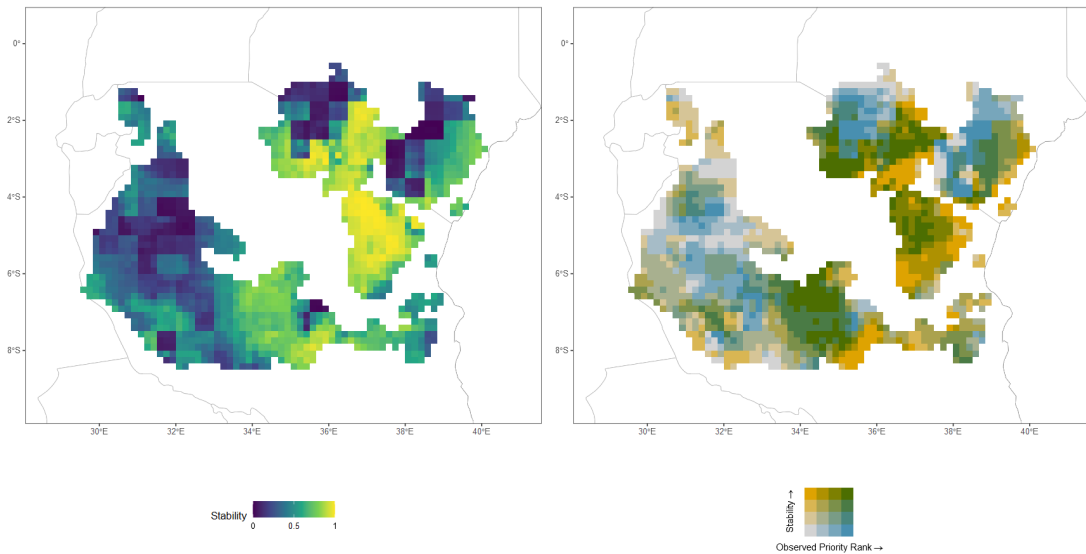


Figure 5.27: The ecological stability output for Masai giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, Masai giraffe range areas in eastern Tanzania and those near the Tanzania-Kenya border rank highly at all warming levels, even when the analysis is extended to areas of external refugia. These areas also have some of the highest stability compared to other areas within the Masai giraffe's geographic range. The Tsavo West and Serengeti NP are key conservation areas, ranking highly across warming levels. Several protected areas, such as Katavi and Tsavo East NP have lower priority ranks at higher warming levels and may therefore need higher adaptation effort than other range areas to support giraffe populations under global warming.

5.3.6 South African giraffe (*Giraffa giraffa giraffa*)

Core Zonation analysis

Priority areas for South African giraffe shift across the global warming levels (Figure 5.28). High priority areas shift southwards and the range within Botswana loses rank at higher warming levels. Only 1.4% of the South African giraffe's geographic range ranks in the top 10% across all warming levels. These areas are found in the southeastern portion of the range, within South Africa. This same area, however, is also the only range area where cells rank consistently in the bottom 10%.

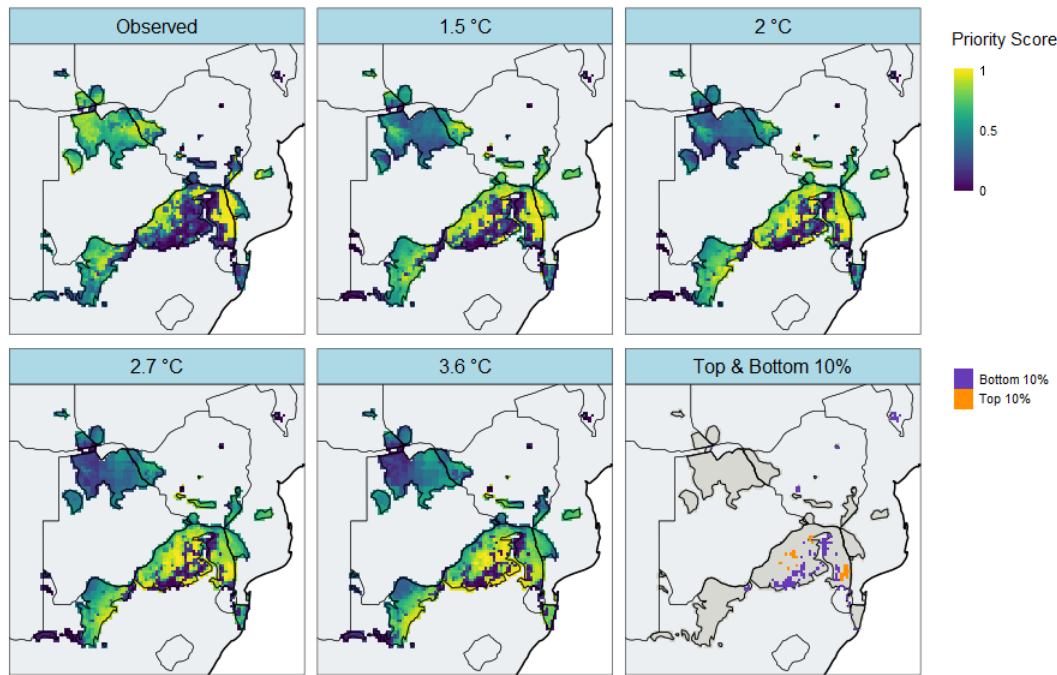


Figure 5.28: South African giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower priority ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

Almost 50% of cells in the South African giraffe's range are unprotected, and many of these cells rank in the top 10% in each of the warming scenarios (Figure 5.29). Internationally designated PAs, which account for ~10% of cells, have a low median rank in all but the observed Zonation run. Nationally designated GMPAs account for some of the top 10% ranking cells across all Zonation runs, as do some of the shared governance cells. When the average value of specific PAs was examined, there are several that ranked in the top 25% priority across all Zonation runs: Kruger NP and Tembe Elephant Park, both in South Africa (Table 5.11). Both Hwange and Luengue-Luiana NP rank in the bottom 50% at 3.6°C, whilst Limpopo NP retains a ranking of almost 0.7 at 3.6°C. The declining rank of these two PAs is likely explained by the concurrent reduction in climate suitability for Southern giraffe, declining species richness for both Acacia and non-Acacia browse, and substantial increase in the maximum duration of extreme drought. Limpopo National Park is projected to experience similar trends; however, at 3.6°C it retains comparatively higher climatic suitability for southern giraffe and higher food-plant species richness, which likely explains its higher overall rank.

Table 5.11: A selection of Protected Areas within the geographic range of South African giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Kruger	National Park	0.92	0.92	0.90	0.85	0.79	South Africa
Hwange	National Park	0.72	0.72	0.58	0.52	0.48	Zimbabwe
Luengue-Luiana	National Park	0.65	0.50	0.40	0.33	0.30	Angola
Limpopo	National Park	0.81	0.87	0.81	0.73	0.68	Mozambique
Tembe Elephant Park	Nature Reserve	0.91	0.78	0.76	0.77	0.85	South Africa

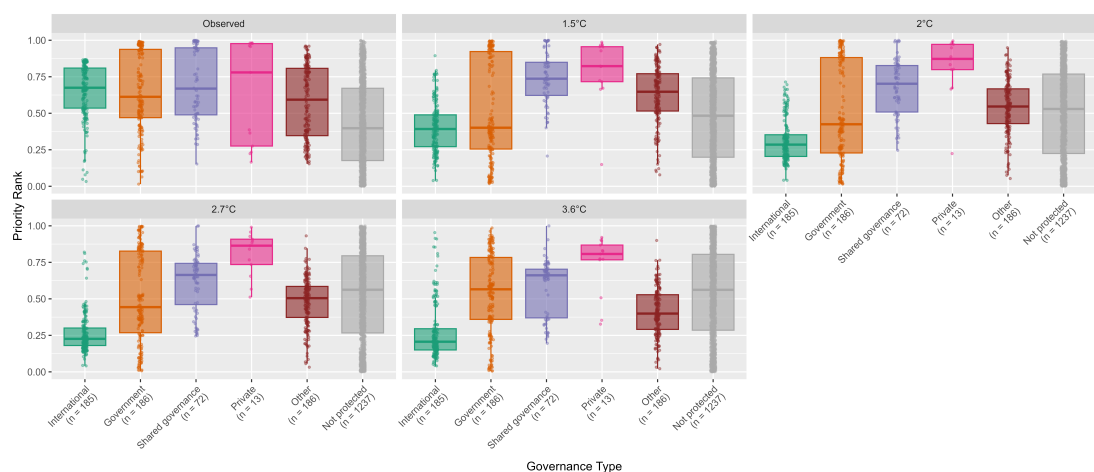


Figure 5.29: The priority rank for each cell ($n = 1,879$) in the South African giraffe core Zonation analysis, organised by Protected area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas).

Extended Zonation analysis

Areas of climate refugia outside of South African giraffe's geographic range do not rank highly until 3.6°C global warming (Figure 5.30). In the Observed period, areas within the current range have a higher median rank than those outside, at 0.69 and 0.3, respectively. Above 1.5°C warming, this is not the case, and by 3.6°C, the median value in areas of climate refugia outside the range is 0.73 compared to 0.47 within the range. As with the

core Zonation runs, the only cells which rank in the top and bottom 10% across all warming levels are those in the eastern parts of South Africa.

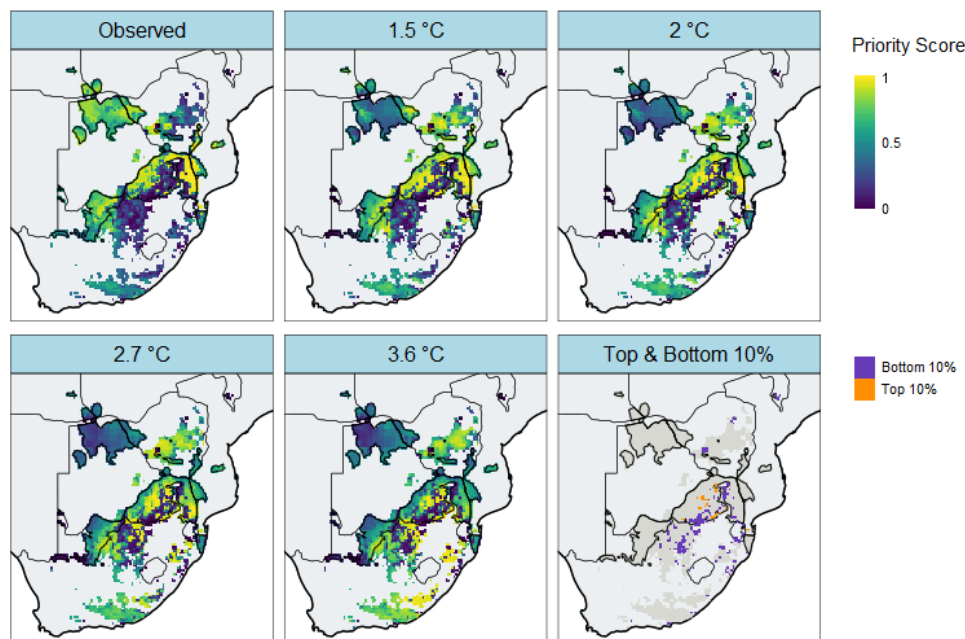


Figure 5.30: Zonation analysis outputs for South African giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the South African giraffe's geographic range and areas of external climate refugia for Southern giraffe (of which South African giraffe are a subspecies)

Ecological stability analysis

The ecological stability analysis shows that many of the areas which rank as most stable are in the eastern part of the South African giraffe's range (Figure 5.31). Very few of these areas overlap with the highest ranking cells of the observed period Zonation run.

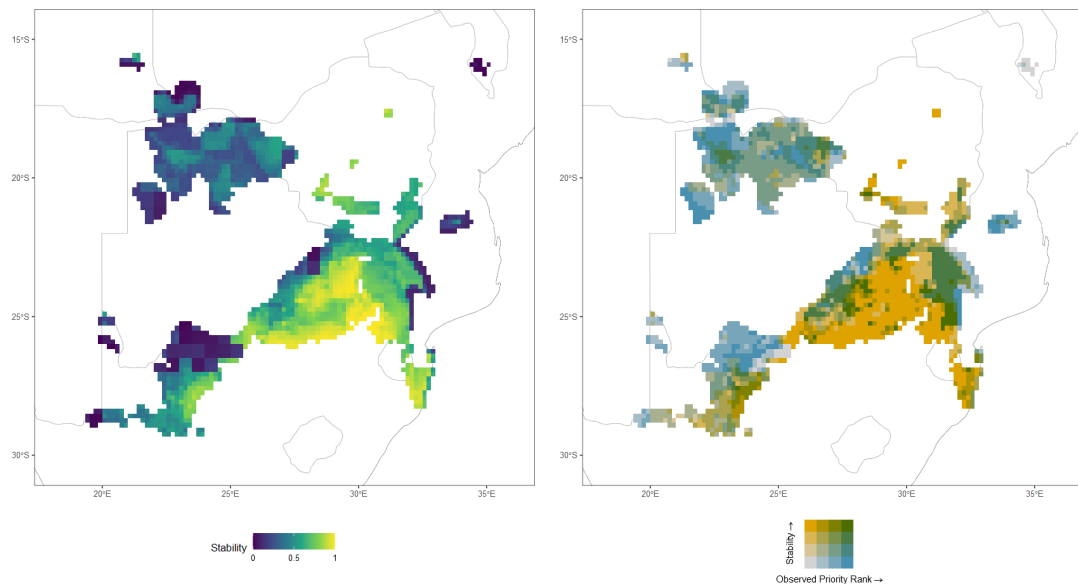


Figure 5.31: The ecological stability output for South African giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, the South African giraffe range area in eastern South Africa is a key conservation priority, being ranked in the top 10 % across all Zonation runs. This area also has a higher stability ranking under 3.6°C. Kruger NP ranks highly even at 3.6°C global warming and may therefore remain more suitable for South African giraffe compared to other areas within their current geographic range. Some NPs, such as Hwange NP in Zimbabwe are ranked poorly at increasing warming levels and may therefore require higher adaptation effort compared to other range areas to support giraffe populations under global warming. Government-managed and privately managed protected areas cover some of the high ranking cells at all levels of warming, but many are unprotected at all warming levels. Areas of external climate refugia rank poorly in South Africa except at the highest global warming levels and therefore may not be suitable for extralimital translocations. However, external refugia within Zimbabwe ranks highly across global warming levels.

5.3.7 Angolan giraffe (*Giraffa giraffa angolensis*)

Core Zonation analysis

In the observed period, within the Angolan giraffe's range, the highest ranking areas are within Botswana and to the north of Namibia (Figure 5.32). This shifts at almost every global warming level, and by 3.6°C global warming, the highest ranking areas are in central and

South Namibia, and the Angolan giraffe range within Botswana has a low rank. Only two areas were flagged as being ranked consistently in the top 10% across all warming levels – one area within the Otjitanda Community Conservancy, near the Angolan border; and one area to the south of the range in Namib-Naukluft NP. These consistent priority areas amount to only 0.5% of the entire Angolan giraffe's geographic range. Areas which ranked consistently poorly are to the east of Namibia. These areas amount to 5.5% of the Angolan giraffe's geographic range.

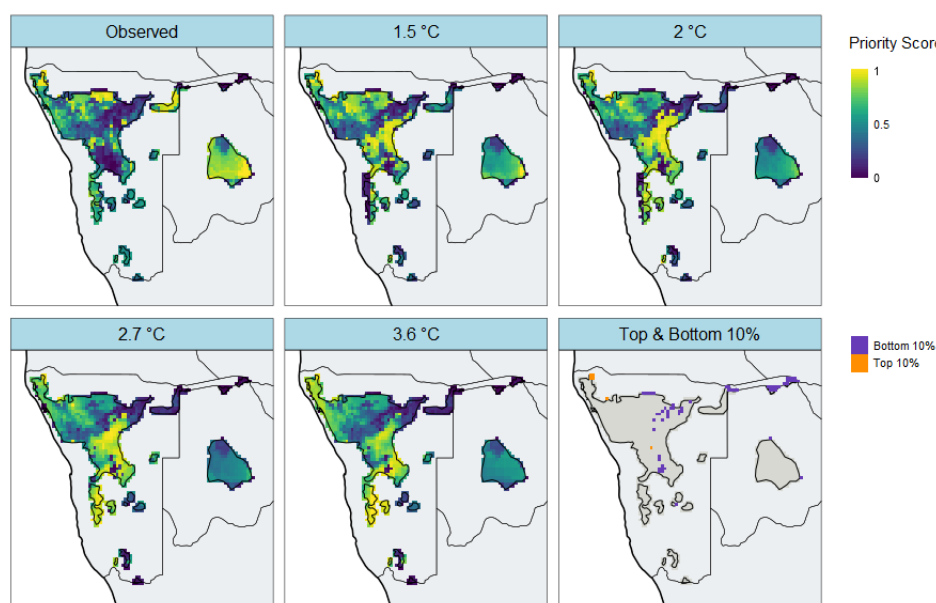


Figure 5.32: Angolan giraffe core Zonation outputs. Yellow indicates a high priority ranking and dark blue shows a lower ranking. For the Top and Bottom 10% map, orange shows areas of consistently high priority, and purple shows areas of consistently low priority.

Most of the cells which rank highly across Zonation runs are either unprotected, nationally designated and government managed, or nationally designated and ICCA-managed (Figure 5.33). Many of the cells with these designations do, however, also rank poorly in each Zonation run. Out of the protected areas examined in Table 5.12, Puros Communal Conservancy in Namibia has the highest average rank at 3.6°C. of 0.86. This PA, along with Sesfontein Communal Conservancy, are the only two that gain average rank at higher warming levels. Examination of the input data layers shows that both of these PAs are projected to experience longer periods of severe drought and reduced climatic suitability for southern giraffe, while retaining broadly similar levels of Acacia and non-Acacia browse species richness across all warming levels. Their increasing rank is therefore most likely driven by the relatively greater projected losses of plant species richness and suitable

giraffe climate elsewhere in the species' range. Supporting this interpretation, Etosha National Park, Khaudum National Park, and the Central Kalahari Game Reserve all decline in rank with increasing global warming. Although they are all projected to have relatively high plant species richness and giraffe climate suitability in the observed scenario, all three are projected to undergo substantial declines in these variables by 3.6°C warming, ultimately reaching values lower than those projected for Puros and Sesfontein.

Table 5.12: A selection of Protected Areas within the geographic range of Angolan giraffe, which are confirmed to have giraffe present, and the average Zonation value across the protected area.

Name	Designation	Observed	1.5°C	2°C	2.7°C	3.6°C	Country
Etosha	National Park	0.72	0.74	0.63	0.55	0.55	Namibia
Central Kalahari	Game Reserve	0.78	0.58	0.49	0.41	0.45	Botswana
Khaudum	National Park	0.85	0.46	0.25	0.20	0.16	Namibia
Sesfontein	Communal Conservancy	0.51	0.50	0.54	0.62	0.71	Namibia
Puros	Communal Conservancy	0.60	0.54	0.59	0.67	0.86	Namibia

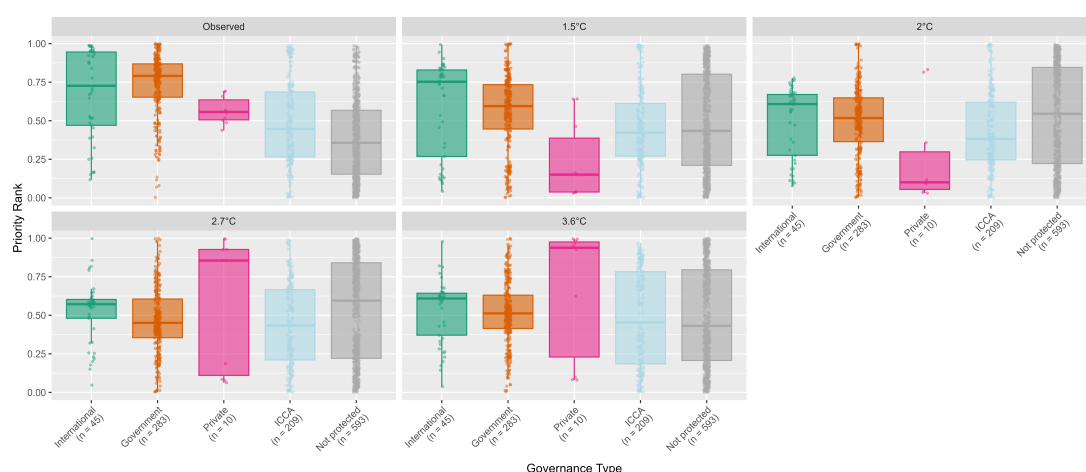


Figure 5.33: The priority rank for each cell ($n = 1,140$) in the Zonation analysis, organised by Protected area designation and management type. Categories are split into Internationally designated (Ramsar sites, UNESCO Man and Biosphere Reserves, UNESCO World Heritage Sites) or Nationally designated. Nationally designated sites are then split into IUCN governance types: Government, Shared governance, Private governance, ICCAs (Indigenous and Community Conserved Areas).

Extended Zonation analysis

When the Zonation runs are extended to include areas of nearby climate refugia, the same pattern emerges, with southern and central Namibia ranking the highest at 3.6°C global warming (Figure 5.34). In this extended Zonation run, the median rank is highest within current Angolan giraffe range until 2°C warming. From this warming level up to 3.6°C warming, the median Zonation rank is highest in areas of external climate refugia, at 0.79 compared to 0.47 inside the subspecies' geographic range, at 3.6°C global warming.

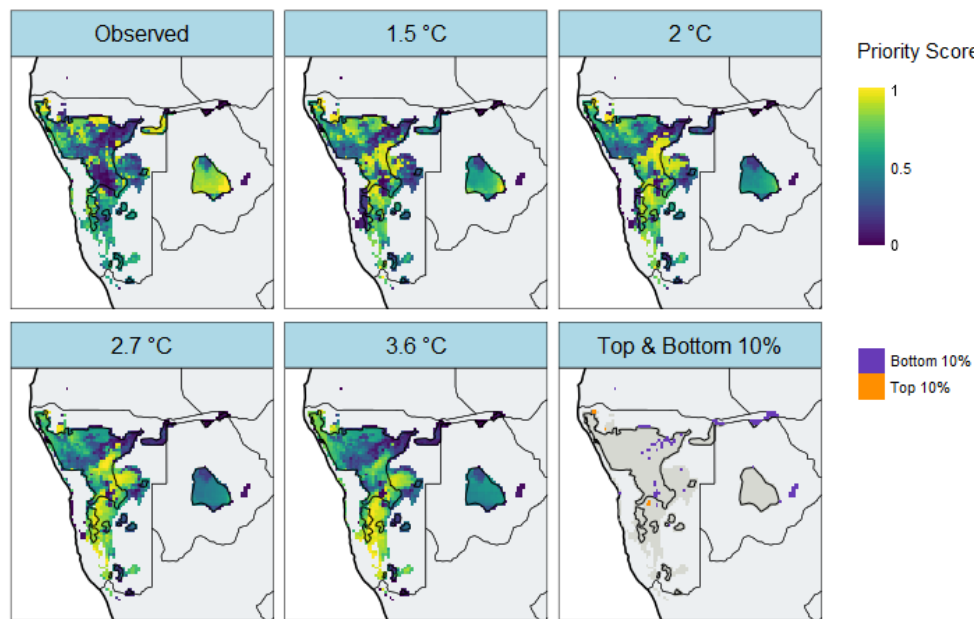


Figure 5.34: Zonation analysis outputs for Angolan giraffe across the five scenarios and showing areas of consistently high or low priority. The analysis was run across the Angolan giraffe's geographic range and areas of external climate refugia for Southern giraffe (of which Angolan giraffe are a subspecies)

Ecological stability analysis

The ecological stability of areas within the Angolan giraffe's range is strongest in central and western Namibia (Figure 5.35). The range in Botswana ranks lowest out of the entire range. The bivariate map shows little overlap between areas that rank highest in stability and those that rank highest in the observed period Zonation run.

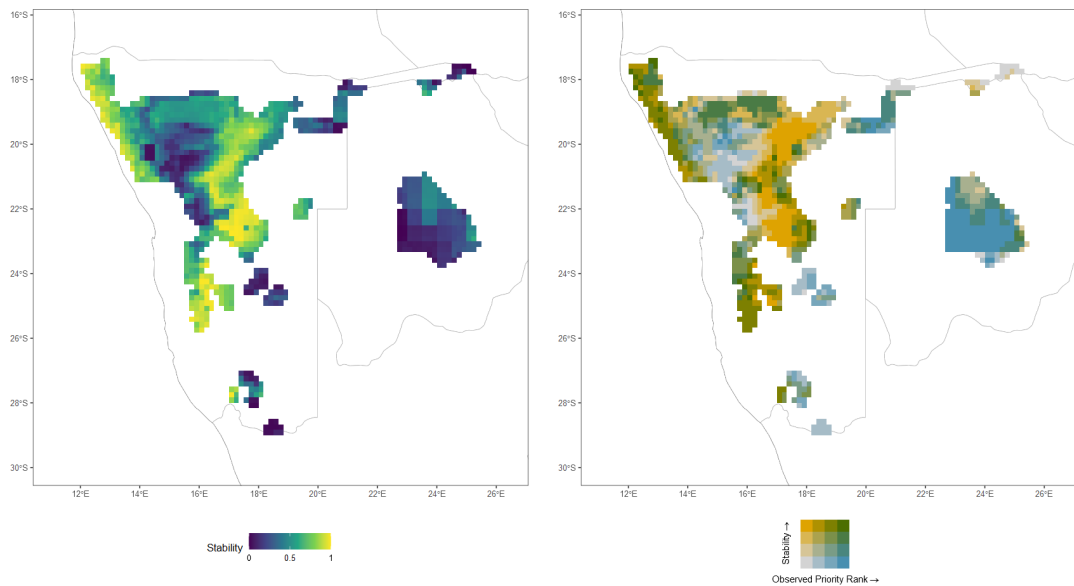


Figure 5.35: The ecological stability output for Angolan giraffe (left) and bivariate map showing stability against the Zonation output for the observed time period (right)

In summary, for Angolan giraffe, the only areas which rank in the top 10% across warming levels are in central and northwestern Namibia, with eastern Namibia and northern Botswana ranking consistently low. These low priority areas also rank poorly on the stability analysis. Across all warming scenarios, high priority areas are found in both Government-managed and ICCA-managed PAs, as well as unprotected areas. At higher global warming levels, areas of external climate refugia increase in priority rank, along with areas to the south of the Angolan giraffe range.

5.4 Discussion

Effective, long-term conservation requires research that goes beyond identifying areas of suitable climate for species at projected global warming levels. The potential impacts from worsening extreme events, disruptions to biotic interactions, and co-occurring anthropogenic threats are important considerations for spatially explicit conservation actions. In this analysis, by using spatial planning software to integrate climate suitability and other factors relevant for species survival, priority conservation areas for giraffe (sub)species have been identified. The highest ranking areas have the best available balance within each giraffe (sub)species' range of climate suitability for giraffe, food availability and the least threats. Additionally, identifying areas that are a high priority

across all scenarios or high priority in the ecological stability analysis highlights which areas are potentially more robust for giraffe under higher levels of global warming. These results provide conservation practitioners with a useful guide on which areas may be most able to support giraffe populations under a changing climate, and those which may need additional support in climate change adaptation or human impact reduction.

5.4.1 Species-specific conservation priorities

Performing Zonation analyses at the subspecies rather than species rank highlighted key differences in conservation priority areas and consequently, the required conservation actions for each species and subspecies. For some (sub)species, such as Kordofan, Nubian, Reticulated, and South African giraffe, protected areas (PAs) may be an important conservation tool and provide a relative buffer against climatic and anthropogenic impacts. For West African giraffe, however, the highest priority areas are outside of PAs.

Priority areas for each giraffe (sub)species shifted under increasing global warming levels. This finding is consistent with many studies which use spatial planning software to prioritise species conservation under climate change (for example, Smith *et al.*, 2016; Triviño *et al.*, 2018; Critchlow *et al.*, 2022), and is likely driven by shifting climate suitability for giraffe and their browse. Despite this, areas of consistently high priority were found in all (sub)species' current geographic ranges, covering between 0.5-9% of each (sub)species' range. Identifying areas which remain a high priority across all scenarios follows the same principle as identifying climate refugia; it provides a guide to direct conservation investments towards areas most likely to remain suitable for giraffe, regardless of the future realised global warming level.

5.4.2 Conservation priorities and Protected Areas

Priority rankings within PAs varied, with some (sub)species having a higher median Zonation rank outside of PAs compared to within. Many giraffe live outside of PAs (O'Connor *et al.*, 2019) and some of these unprotected areas appear to be potential priorities for giraffe conservation. For example, in Niger, an unprotected area north of Niamey has a high ranking for West African giraffe (see Figure 5.9). Following Target 3 of the Kunming-Montreal Global Biodiversity Framework (Convention on Biological

Diversity, 2022), to protect at least 30% of land, water and sea by 2030, there is potential for PA expansion within the decade. Understanding which areas are a priority for giraffe conservation may help in identifying which areas to protect (Watson *et al.*, 2023).

Not only did some unprotected areas rank highly, but many PAs had a low priority rank, with some ranking in the bottom 10% across all global warming levels. An example of this is Zakouma NP in Chad which has a low priority rank across global warming levels (see Table 5.7). In these areas, long-term plans for giraffe conservation should assess projections of extreme events and resource availability to plan adaptation measures accordingly, or consider translocations outside of the PA. Climate change adaptation planning is becoming more commonplace in PA management (Gillingham *et al.*, 2024). Adaptations depend on the target species and ecosystem, but include providing shaded areas, artificial waterholes, and restoration of climate change-resilient plant species.

For all species and subspecies except West African giraffe, at least some of the areas ranking in the top 10% across global warming scenarios are within PAs. These PAs should be considered conservation priority areas for giraffe, as they are projected to be relatively buffered against climatic and anthropogenic pressures compared to other range areas. For example, Tsavo West NP in Kenya ranks highly for Masai giraffe (see Table 5.10), and given its protected status, it is likely to be a key area for Masai giraffe under climate change. PAs have been shown to act as a buffer against increasing warming levels compared to areas which have been converted to cropland (Xu *et al.*, 2022), highlighting the importance of these areas for species. Where PAs are relatively buffered from the negative impacts of climate change, conservation efforts should also look to ensure adequate connectivity to facilitate species movement into the PA (Hannah, 2008).

It is also important to note that within PAs, priority rankings varied among different designation and governance types. For Reticulated giraffe, government-managed and ICCA-managed PAs included some of the highest-ranking sites across warming levels. For South African giraffe, privately governed PAs had the highest median priority rankings across all warming levels, whereas internationally designated PAs consistently had the lowest median rankings. Conversely, for Angolan giraffe, internationally designated PAs had consistently higher median rankings than both nationally designated government-managed PAs and ICCA-managed areas. These results indicate that priority

ranks are not uniformly distributed across PA types. This could reflect differences in land management and the level of anthropogenic disturbance permitted within different PA categories, however, given the mixed patterns observed and the absence of a causal analysis in this study, further work would be required to identify any underlying mechanisms.

When interpreting the results of this analysis, it is important to consider that the Zonation models may have favoured PAs through the proxy of the gHM layer, which adds weight to areas with less human modification. However, a 2018 study found that, whilst overall human footprint is almost half the global average within PAs, 32% of protected land is under intense human pressures, with some PAs within Africa under some of the highest human pressure (Jones *et al.*, 2018). Additionally, given the variation in priority rankings seen across PAs, it is unlikely that there was a strong bias towards these areas.

5.4.3 Extralimital conservation potential

The conservation priority rankings in areas of external climate refugia (outside of the (sub)species' current geographic range) varied across (sub)species and scenarios. Where median priority rankings were higher within species' current geographic range compared to external refugia, conservation efforts may be more effective when focused on protecting and managing existing habitats. For Masai giraffe, external refugia had a lower median rank than within their geographic range at all warming levels. For West African giraffe, however, the median rank was higher within the subspecies' range. For Kordofan, South African, and Angolan giraffe, the higher median priority rank shifted depending on the level of global warming. Additionally, some (sub)species showed areas of consistently high priority outside of their current geographic range, indicating possible benefits from considering range expansion or assisted translocations. Species translocations are a common conservation tool, but few have yet been done for the sole purpose of climate-change adaptation (Butt *et al.*, 2021).

Whilst this chapter did not directly compare internal climate refugia with priority rankings, the inclusion of external climate refugia in the extended study area offers some insight into how incorporating additional factors can influence the relative suitability of refugia under climate change. Notably, some areas of external climate refugia consistently ranked in the

bottom 10% across all warming scenarios, reinforcing the importance of incorporating factors beyond mean climate and considering multiple climatic and anthropogenic threats in tandem. Increasingly, it has been noted that further research and management plans are needed for areas of climate refugia, given the potential of concurrent climatic or anthropogenic stressors (Keppel *et al.*, 2024). As such, more research has attempted to integrate factors beyond changes in mean climate, to identify the most robust refugia against multiple stressors (Ebersole *et al.*, 2020; Rojas *et al.*, 2022). The integration of these additional stressors has been coined 'Anthropocene refugia', given the importance of considering human impacts in designating conservation areas (Monsarrat *et al.*, 2019). Further comparisons of species-specific climate change refugia and Zonation rankings can be found in Chapter 7 – 'Conservation Implications, Limitations, and Conclusions'.

5.4.4 Ecological stability

The ecological stability analysis provides a useful accompaniment to the general zonation outputs by identifying areas projected to undergo the least anthropogenic, biotic, and climatic change under the highest global warming scenario. Previous research using similar approaches have combined current measures of habitat intactness with projections of biome shifts (Eigenbrod *et al.*, 2015) or changes to mean climate (Watson *et al.*, 2013). Other studies convert temporal stability into spatial metrics using 'climate velocity' – the distance to the nearest cell with the same climate at future warming levels (Hamann *et al.*, 2015). Using this metric in spatial prioritisation analyses can identify areas where species need to migrate the least distance to maintain suitable climate (Lai *et al.*, 2022). Whilst these outputs are highly useful for conservation, many focus on one metric of change. The ecological stability analyses in this Chapter instead provide a nuanced assessment of the projected ecological stability of an area. The outputs should, however, be evaluated alongside the outputs of the core zonation analyses. Areas ranked highly in both analyses are particularly important for conservation because they have the best long-term stability, alongside the best available observed distribution of resources compared to threats.

5.4.5 Using spatial prioritisation software to assess projected climate change and additional anthropogenic impacts

Integrating extreme climate and non-climatic factors into Zonation analyses provides a novel approach to identifying the best areas for terrestrial species conservation within a predefined range. A 2016 review found that only 46 papers had incorporated climate change into spatial conservation prioritisation (Jones *et al.*, 2016), 41 of which used outputs from species distribution models. Many spatial prioritisation studies focus on PAs, including using PA status as a feature in spatial prioritisation analyses with the aim of identifying candidate areas for the expansion of PA networks (for example Graham *et al.*, 2019; Haight and Hammill, 2020; Stralberg *et al.*, 2020). Recently, more research is factoring climate change into spatial prioritisation analyses but using climatic factors other than changes in mean climate is still infrequent.

Instead of spatial prioritisation methods, some studies integrate anthropogenic and biotic factors directly into SDMs to project species distributions based on the combined impacts of climate change, biotic interactions, and human population changes (for example climate extremes: Ebrahimi *et al.*, 2023; Fonteyn *et al.*, 2025; human pressures: Frans and Liu, 2024; Zhang *et al.*, 2024; biotic interactions: Cosentino *et al.*, 2023; Zhang *et al.*, 2024). However, using SDM outputs as input layers within spatial prioritisation analyses offers greater flexibility to explore the relative influence of different features. These results are often more interpretable for conservation decision-making, particularly when identifying relative priorities across a defined landscape. Spatial prioritisation methods such as Zonation can separately incorporate climate suitability, threat, and resource availability layers, making it easier to understand what drives conservation value in a given area. This is particularly valuable for PA management, where targeted actions can enhance resilience and adaptation to climate change (Gillingham *et al.*, 2024).

5.4.6 Limitations

Due to the complexity of climate change impacts and ecological interactions, there are factors not accounted for in this analysis which may indirectly impact giraffe, and therefore affect the priority rankings. For example, research has shown that the impact of lion predation on giraffe can be mitigated by increased abundance of other prey species

(Davidson *et al.*, 2013; Lee *et al.*, 2016). Climate suitability for other lion prey species was not included in this analysis because of the uncertainties surrounding the strength and spatial consistency of this interaction, as well as the need to account for prey abundance rather than simply 'presence' (or climate suitability). Similarly, many factors could affect the availability and quality of giraffe forage and suitable habitat. Changes to fire regimes and the impact of rising atmospheric CO₂ levels on plants under increasing global warming could alter biomes and lead to shifts in dominant vegetation types (Bond and Keeley, 2005; Keeley and Syphard, 2016; Martens *et al.*, 2021).

A limitation of the Zonation software itself lies in the interpretation of the hierarchical ranking system. Firstly, given the constant linear ranking from 0-1 across the study area, the rank value does not give an indication of the scale of difference between two adjacently ranking cells, only that the cell with the lower rank was the 'next best option'. Secondly, it may be easily assumed that because a cell ranks highly, that it is suitable for giraffe, but the rank values only represent which cells hold the best balance between positive and negative inputs given the distribution of values within the study area. This is different from indicating survival probability of giraffe in these cells and should therefore not be interpreted as such. For example, if a hypothetical study area had climate suitability values of between 0 and 0.2 (out of a maximum value of 1), the cells with a value of 0.2 would be ranked highest, despite none of the cells actually being suitable. This is particularly prudent to note when looking at higher global warming scenarios where conditions are likely to be less favourable. Both of these caveats can be reasonably mitigated through the interpretation of Zonation values alongside the original input data to ensure the values within the cells are suitable.

5.4.7 Conclusion

This chapter has identified areas within each giraffe (sub)species' geographic range that are projected to be more resilient to climatic and anthropogenic pressures under multiple levels of global warming. The finding that some areas of giraffe climate refugia have a low priority conservation rank has highlighted the importance of considering multiple factors alongside climate suitability. For some (sub)species, areas of refugia outside of their current geographic range rank more highly than within their geographic range, suggesting

that assisted migration and translocations may be key for these (sub)species under higher global warming levels. PAs were found to be an important conservation tool for most species and subspecies of giraffe, but some outperform others, and adaptive management plans may be needed to ensure long-term survival of giraffe in these areas. High conservation priority areas which do not have protected status should be considered as potential candidates for PA expansion. In the next chapter, the GiraffeClim web application is introduced, which enables users to explore the outputs of the Zonation analyses alongside the input data, facilitating a more in-depth understanding of the drivers behind the priority rankings where desired.

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Supplementary Material

This section contains the supplementary material for Chapter 5 ‘Beyond mean climate: A comprehensive approach to prioritising areas for giraffe conservation under climate change’.

Giraffe forage species

A list of giraffe forage species was obtained from the literature (Table S5.1). Where plant taxonomy had been updated since the published literature, Plants of the World Online (POWO, 2024) was used to update the species name so that records matched with the taxonomy used in the Wallace Initiative.

Table S5.1: The list of plant species used in the Zonation analyses and literature sources (reference) which mention the plant species as a food source for giraffe. The name of the plant as mentioned in the literature is shown by ‘Species’, and is accompanied by the currently accepted species name. ‘Giraffe (sub)species’ is the confirmed or likely (sub)species of giraffe from the studies referenced. Where the species was not explicitly mentioned in the literature source, assumptions of species were made using the location of the study area.

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Acacia abyssinica</i>	<i>Vachellia abyssinica</i>	Masai	Pratt and Anderson (1982)
<i>Acacia drepanolobium</i>	<i>Vachellia drepanolobium</i>	Reticulated	Birkett and Stevens-Wood (2005)
<i>Acacia elatior</i>	<i>Vachellia elatior</i>	Masai	Leuthold and Leuthold (1972)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Acacia erioloba</i>	<i>Vachellia edgeworthii</i>	South African	Deacon and Smit (2017); Deacon <i>et al.</i> (2023)
<i>Acacia erubescens</i>	<i>Senegalia erubescens</i>	South African	Sauer <i>et al.</i> (1977); Furstenburg and van Hoven (1994)
<i>Acacia exuvialis</i>	<i>Vachellia exuvialis</i>	South African	Hall-Martin (1975); Furstenburg and van Hoven (1994)
<i>Acacia gerrerdii</i>	<i>Vachellia gerrardii</i>	Masai	Pellew (1984b)
<i>Acacia hereroensis</i>	<i>Senegalia hereroensis</i>	South African	Hall-Martin (1975)
<i>Acacia hockii</i>	<i>Vachellia hockii</i>	Masai	Pellew (1984a)
<i>Acacia karroo</i>	<i>Vachellia karroo</i>	South African	Parker <i>et al.</i> (2003); Parker and Bernard (2005)
<i>Acacia mellifera</i>	<i>Senegalia mellifera</i>	Masai; South African	Waweru and Githaiga (2014); Deacon and Smit (2017); Levi <i>et al.</i> (2022); Deacon <i>et al.</i> (2023)
<i>Acacia nigrescens</i>	<i>Senegalia nigrescens</i>	South African	Hall-Martin (1974, 1975); Furstenburg and van Hoven (1994); Fleming <i>et al.</i> (2006)
<i>Acacia nilotica</i>	<i>Vachellia nilotica</i>	South African; West African	Hall-Martin (1975); Caister <i>et al.</i> (2003)
<i>Acacia robusta</i>	<i>Vachellia robusta</i>	South African	Furstenburg and van Hoven (1994)
<i>Acacia senegal</i>	<i>Senegalia senegal</i>	Masai; South African; West African	Hall-Martin (1975); Pellew (1984a); Caister <i>et al.</i> (2003); Strauss <i>et al.</i> (2015)
<i>Acacia senegalensis</i>	<i>Senegalia senegal</i>	West African	Caister <i>et al.</i> (2003)
<i>Acacia seyal</i>	<i>Vachellia seyal</i>	West African	Caister <i>et al.</i> (2003)
<i>Acacia sieberiana</i>	<i>Acacia terminalis</i>	Masai; West African	Pratt and Anderson (1982); Caister <i>et al.</i> (2003)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Acacia tortilis</i>	<i>Vachellia tortilis</i>	Masai; South African	Leuthold and Leuthold (1972); Sauer <i>et al.</i> (1977); Pellew (1984a); Furstenburg and van Hoven (1994); Waweru and Githaiga (2014)
<i>Acacia welwitschii</i>	<i>Senegalia welwitschii</i>	South African	Furstenburg and van Hoven (1994)
<i>Acacia xanthophloea</i>	<i>Vachellia xanthophloea</i>	Masai; Rothschild; South African	Pratt and Anderson (1982); Pellew (1984a); Furstenburg and van Hoven (1994); Brenneman <i>et al.</i> (2009); Strauss <i>et al.</i> (2015); Mahenya <i>et al.</i> (2016)
<i>Albizia amara</i>	<i>Albizia amara</i>	Masai	Pellew (1984b)
<i>Albizia harveyi</i>	<i>Albizia harveyi</i>	Masai; South African	Hall-Martin (1975); Pellew (1984b)
<i>Astripomea hyoscyamoide</i>	<i>Astripomoea hyoscyamoides</i>	Masai	Waweru and Githaiga (2014)
<i>Azima tetracantha</i>	<i>Azima tetracantha</i>	South African	Parker <i>et al.</i> (2003)
<i>Balanites aegyptiaca</i>	<i>Balanites aegyptiaca</i>	Masai; West African	Pellew (1984a, 1984b); Caister <i>et al.</i> (2003); Levi <i>et al.</i> (2022)
<i>Barleria taitensis</i>	<i>Barleria taitensis</i>	Masai	Waweru and Githaiga (2014)
<i>Bauhinia taitensis</i>	<i>Bauhinia taitensis</i>	Masai	Waweru and Githaiga (2014)
<i>Bolusanthus speciosus</i>	<i>Bolusanthus speciosus</i>	South African	Hall-Martin (1975)
<i>Boscia coriacea</i>	<i>Boscia coriacea</i>	Masai	Leuthold and Leuthold (1972)
<i>Buddleja saligna</i>	<i>Buddleja saligna</i>	South African	Parker <i>et al.</i> (2003)
<i>Calyptrorhiza taitensis</i>	<i>Calyptrorhiza taitensis</i>	Masai	Leuthold and Leuthold (1972)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Canthium spinosum</i>	<i>Catunaregam spinosa</i>	South African	Parker and Bernard (2005)
<i>Carissa edulis</i>	<i>Carissa spinarum</i>	Masai	Pratt and Anderson (1982)
<i>Carissa spinarum</i>	<i>Carissa spinarum</i>	Masai	Levi <i>et al.</i> (2022)
<i>Cassia abbreviate</i>	<i>Cassia abbreviata</i>	Masai	Waweru and Githaiga (2014)
<i>Colophospermum mopane</i>	<i>Colophospermum mopane</i>	South African	Hall-Martin (1974, 1975)
<i>Combretum apiculatum</i>	<i>Combretum apiculatum</i>	South African	Hall-Martin (1974, 1975); Sauer <i>et al.</i> (1977)
<i>Combretum glutinosum</i>	<i>Combretum glutinosum</i>	West African; West African	Caister <i>et al.</i> (2003)
<i>Combretum hereroense</i>	<i>Combretum hereroense</i>	South African	Hall-Martin (1974, 1975); Sauer <i>et al.</i> (1977)
<i>Combretum imberbe</i>	<i>Combretum imberbe</i>	South African	Hall-Martin (1974, 1975); Sauer <i>et al.</i> (1977); Furstenburg and van Hoven (1994)
<i>Combretum zeyheri</i>	<i>Combretum zeyheri</i>	Masai; South African	Hall-Martin (1974, 1975); Levi <i>et al.</i> (2022)
<i>Cordia ovalis</i>	<i>Cordia ovalis</i>	Masai	Pellew (1984a)
<i>Croton macrostachyus</i>	<i>Croton macrostachyus</i>	Masai	Pratt and Anderson (1982)
<i>Dichrostachys cinerea</i>	<i>Dichrostachys cinerea</i>	Masai; South African	Furstenburg and van Hoven (1994); Levi <i>et al.</i> (2022)
<i>Diospyros mespiliformis</i>	<i>Diospyros mespiliformis</i>	South African	Hall-Martin (1974, 1975)
<i>Dodonaea viscosa</i>	<i>Dodonaea viscosa</i>	Masai	Pratt and Anderson (1982); Mahenya <i>et al.</i> (2016)
<i>Euclea divinorum</i>	<i>Euclea divinorum</i>	Masai	Pratt and Anderson (1982); Mahenya <i>et al.</i> (2016)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Euclea undulata</i>	<i>Euclea undulata</i>	South African	Hall-Martin (1974, 1975); Parker <i>et al.</i> (2003); Parker and Bernard (2005)
<i>Euphorbia scheffleri</i>	<i>Euphorbia scheffleri</i>	Masai	Leuthold and Leuthold (1972)
<i>Faidherbia albida</i>	<i>Faidherbia albida</i>	West African	Caister <i>et al.</i> (2003)
<i>Ficus natalensis</i>	<i>Ficus natalensis</i>	Masai	Levi <i>et al.</i> (2022)
<i>Grewia bicolor</i>	<i>Grewia bicolor</i>	Masai	Pellew (1984a); Strauss <i>et al.</i> (2015)
<i>Grewia fallax</i>	<i>Grewia arborea</i>	Masai	Pellew (1984a); Strauss <i>et al.</i> (2015)
<i>Grewia retinervis</i>	<i>Grewia retinervis</i>	South African	Deacon and Smit (2017)
<i>Grewia similis</i>	<i>Grewia similis</i>	Nubian	Gitau <i>et al.</i> (2024)
<i>Grewia subspathulata</i>	<i>Grewia subspathulata</i>	South African	Hall-Martin (1974)
<i>Grewia tembensis</i>	<i>Grewia tembensis</i>	Masai	Waweru and Githaiga (2014)
<i>Grewia villosa</i>	<i>Grewia villosa</i>	Masai	Waweru and Githaiga (2014)
<i>Gymnosporia buxifolia</i>	<i>Gymnosporia buxifolia</i>	South African	Parker <i>et al.</i> (2003)
<i>Hymenodictyon parvqolium</i>	<i>Hymenodictyon parvifolium</i>	Masai	Leuthold and Leuthold (1972)
<i>Lawsonia inermis</i>	<i>Lawsonia inermis</i>	Masai	Leuthold and Leuthold (1972)
<i>Lippia javanica</i>	<i>Lippia javanica</i>	Masai	Pratt and Anderson (1982)
<i>Lonchocarpus capassa</i>	<i>Lonchocarpus capassa</i>	South African	Furstenburg and van Hoven (1994)
<i>Maerua crassifolia</i>	<i>Maerua crassifolia</i>	West African	Caister <i>et al.</i> (2003)
<i>Maerua triphylla</i>	<i>Maerua triphylla</i>	Masai; Nubian	Levi <i>et al.</i> (2022); Gitau <i>et al.</i> (2024)
<i>Maytenus senegalensis</i>	<i>Gymnosporia senegalensis</i>	Nubian; South African	Hall-Martin (1974, 1975); Gitau <i>et al.</i> (2024)
<i>Melia volkensii</i>	<i>Melia volkensii</i>	Masai	Leuthold and Leuthold (1972); Waweru and Githaiga (2014)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Ochna inermi</i>	<i>Ochna inermis</i>	Masai	Waweru and Githaiga (2014)
<i>Ocimum suave</i>	<i>Ocimum gratissimum</i>	Masai	Pratt and Anderson (1982)
<i>Olea africana</i>	<i>Olea europaea</i>	Masai	Pratt and Anderson (1982); Mahenya <i>et al.</i> (2016)
<i>Olea europea</i>	<i>Olea europaea</i>	South African	Parker <i>et al.</i> (2003)
<i>Pappea capensis</i>	<i>Pappea capensis</i>	South African	Parker and Bernard (2005)
<i>Peltophorum africanum</i>	<i>Peltophorum africanum</i>	South African	Sauer <i>et al.</i> (1977)
<i>Phyllanthus sepialis</i>	<i>Phyllanthus sepialis</i>	Masai	Pellew (1984b)
<i>Piliostigma thonningii</i>	<i>Piliostigma thonningii</i>		
<i>Platyceliphium voence</i>	<i>Platycelyphium voense</i>	Masai	Waweru and Githaiga (2014)
<i>Portulacaria afra</i>	<i>Portulacaria afra</i>	South African	Parker and Bernard (2005)
<i>Premna holstii</i>	<i>Premna resinosa</i>	Masai	Leuthold and Leuthold (1972)
<i>Premna oligotricha</i>	<i>Premna oligotricha</i>	Masai	Leuthold and Leuthold (1972)
<i>Premna resinosa</i>	<i>Premna resinosa</i>	Masai	Leuthold and Leuthold (1972)
<i>Prosopis africana</i>	<i>Anonychium africanum</i>	West African	Caister <i>et al.</i> (2003)
<i>Psiadia arabica</i>	<i>Psiadia punctulata</i>	Masai	Pratt and Anderson (1982)
<i>Rhamnus prinoides</i>	<i>Rhamnus prinoides</i>	Masai	Pratt and Anderson (1982)
<i>Rhus crenata</i>	<i>Searsia crenata</i>	South African	Parker and Bernard (2005)
<i>Rhus lancea</i>	<i>Searsia lancea</i>	South African	Sauer <i>et al.</i> (1977)
<i>Rhus longispina</i>	<i>Searsia longispina</i>	South African	Sauer <i>et al.</i> (1977); Parker and Bernard (2005)
<i>Rhus natalensis</i>	<i>Searsia natalensis</i>	Nubian	Gitau <i>et al.</i> (2024)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Rhus pallens</i>	<i>Searsia pallens</i>	South African	Parker <i>et al.</i> (2003); Parker and Bernard (2005)
<i>Salvadora persica</i>	<i>Salvadora persica</i>	Masai	Leuthold and Leuthold (1972)
<i>Schotia afra</i>	<i>Schotia afra</i>	South African	Parker <i>et al.</i> (2003); Parker and Bernard (2005)
<i>Schotia brachypetala</i>	<i>Schotia brachypetala</i>	South African	Hall-Martin (1974, 1975); Furstenburg and van Hoven (1994)
<i>Scolopia zeyheri</i>	<i>Scolopia zeyheri</i>	Masai	Levi <i>et al.</i> (2022)
<i>Scutia myrtina</i>	<i>Scutia myrtina</i>	South African	Parker <i>et al.</i> (2003); Parker and Bernard (2005)
<i>Sideroxylon inerme</i>	<i>Sideroxylon inerme</i>	South African	Parker and Bernard (2005)
<i>Solanum incanum</i>	<i>Solanum incanum</i>	Masai; Nubian	Waweru and Githaiga (2014); Gitau <i>et al.</i> (2024)
<i>Spirostachys africana</i>	<i>Spirostachys africana</i>	South African	Hall-Martin (1974); Sauer <i>et al.</i> (1977)
<i>Strychnos potatorum</i>	<i>Strychnos potatorum</i>	Masai	Levi <i>et al.</i> (2022)
<i>Syzygium guineense</i>	<i>Syzygium guineense</i>	Masai	Pratt and Anderson (1982)
<i>Tarchonanthus camphoratus</i>	<i>Tarchonanthus camphoratus</i>	South African	Parker <i>et al.</i> (2003)
<i>Terminalia prunioides</i>	<i>Terminalia prunioides</i>	South African	Hall-Martin (1974, 1975)
<i>Thunbergia alata</i>	<i>Thunbergia alata</i>	Masai	Pratt and Anderson (1982)
<i>Thylachium thomasii</i>	<i>Thilachium thomasii</i>	Masai	Leuthold and Leuthold (1972)
<i>Turraea robusta</i>	<i>Turraea robusta</i>	Masai	Pratt and Anderson (1982)
<i>Vachellia abyssinica</i>	<i>Vachellia abyssinica</i>	Nubian	Gitau <i>et al.</i> (2024)
<i>Vachellia drepanolobium</i>	<i>Vachellia drepanolobium</i>	Masai	Levi <i>et al.</i> (2022)
<i>Vachellia gerrardi</i>	<i>Vachellia gerrardi</i>	Nubian	Gitau <i>et al.</i> (2024)

Browse spp.	Accepted species name	Giraffe spp.	Reference
<i>Vachellia haemotoxylon</i>	<i>Vachellia haematoxylon</i>	Southern	Viljoen <i>et al.</i> (2017)
<i>Vachellia kirkii</i>	<i>Vachellia kirkii</i>	Masai	Levi <i>et al.</i> (2022)
<i>Vachellia tortilis</i>	<i>Vachellia tortilis</i>	Masai	Levi <i>et al.</i> (2022)
<i>Vachellia xanthophloea</i>	<i>Vachellia xanthophloea</i>	Nubian	Gitau <i>et al.</i> (2024)
<i>Vitex doniana</i>	<i>Vitex doniana</i>		
<i>Warburgia ugandensis</i>	<i>Warburgia ugandensis</i>	Masai	Mahenya <i>et al.</i> (2016)
<i>Ziziphus mauritiana</i>	<i>Ziziphus mauritiana</i>	West African	Caister <i>et al.</i> (2003)
<i>Ziziphus mucronata</i>	<i>Ziziphus mucronata</i>	Masai; South African	Hall-Martin (1975); Sauer <i>et al.</i> (1977); Pellew (1984b); Furstenburg and van Hoven (1994); Levi <i>et al.</i> (2022); Deacon <i>et al.</i> (2023)

Marginal loss rule comparison

Table S5.2: A comparison of the ABF and CAZ2 marginal loss rule (MLR) outputs for each Zonation run, using several metrics. SR is the Spearman's Rank value, which shows the correlation between each MLRs priority rank, and MAD is the Mean Absolute Difference, which is the average difference in priority rank between each MLR across the study extent. The 'Overlap percentage' is the percentage of top and bottom ranking cells which are the same using both MLRs

(Sub)species	Scenario	SR	MAD	Overlap (%)			
				Top 10%	Top 25%	Bottom 10%	Bottom 25%
Angolan	Observed	0.96	0.06	0.74	0.75	0.73	0.75
	1.5	0.88	0.08	0.84	0.75	0.61	0.63
	2.0	0.87	0.07	0.81	0.76	0.51	0.64
	2.7	0.93	0.06	0.80	0.80	0.56	0.72
	3.6	0.96	0.05	0.87	0.84	0.56	0.79
	Stability	0.98	0.05	0.81	0.83	0.74	0.82
Kordofan	Observed	0.95	0.06	0.76	0.78	0.80	0.78
	1.5	0.97	0.04	0.95	0.89	0.85	0.88
	2.0	0.97	0.04	0.89	0.91	0.85	0.91
	2.7	0.98	0.03	0.76	0.96	0.85	0.86
	3.6	0.98	0.03	0.95	0.76	0.85	0.84
	Stability	0.91	0.09	0.67	0.67	0.89	0.73
Masai	Observed	0.98	0.04	0.91	0.82	0.78	0.84
	1.5	0.98	0.04	0.82	0.90	0.80	0.84
	2.0	1.00	0.00	1.00	1.00	1.00	1.00
	2.7	0.99	0.03	0.91	0.91	0.73	0.86
	3.6	0.99	0.03	0.93	0.92	0.70	0.82
	Stability	0.96	0.05	0.91	0.85	0.74	0.79
Nubian	Observed	0.95	0.06	0.88	0.87	0.80	0.62
	1.5	0.97	0.04	0.84	0.91	0.80	0.76
	2.0	0.97	0.05	0.80	0.93	0.84	0.72
	2.7	0.96	0.05	0.91	0.88	0.67	0.72
	3.6	0.94	0.06	0.91	0.91	0.58	0.71
	Stability	0.97	0.03	0.80	0.95	0.61	0.81
Reticulated	Observed	0.95	0.05	0.77	0.70	0.81	0.81

(Sub)species	Scenario	SR	MAD	Overlap (%)			
				Top 10%	Top 25%	Bottom 10%	Bottom 25%
	1.5	0.97	0.04	0.75	0.85	0.78	0.82
	2.0	0.97	0.03	0.88	0.89	0.77	0.80
	2.7	0.98	0.03	0.85	0.88	0.75	0.81
	3.6	0.98	0.03	0.81	0.91	0.63	0.81
	Stability	0.97	0.04	0.66	0.84	0.84	0.82
South African	Observed	0.97	0.04	0.83	0.81	0.80	0.86
	1.5	0.97	0.04	0.90	0.86	0.66	0.80
	2.0	0.97	0.04	0.85	0.85	0.63	0.80
	2.7	0.96	0.04	0.89	0.89	0.63	0.76
	3.6	0.95	0.05	0.94	0.89	0.68	0.76
	Stability	0.97	0.04	0.94	0.92	0.77	0.75
West African	Observed	0.99	0.03	1.00	0.95	0.58	1.00
	1.5	0.98	0.03	1.00	0.89	1.00	0.89
	2.0	0.99	0.02	0.88	1.00	1.00	0.95
	2.7	0.99	0.03	0.88	1.00	0.88	0.89
	3.6	0.98	0.04	0.76	0.80	1.00	0.95
	Stability	0.94	0.06	0.67	0.71	0.76	0.76

Zonation weightings sensitivity analysis

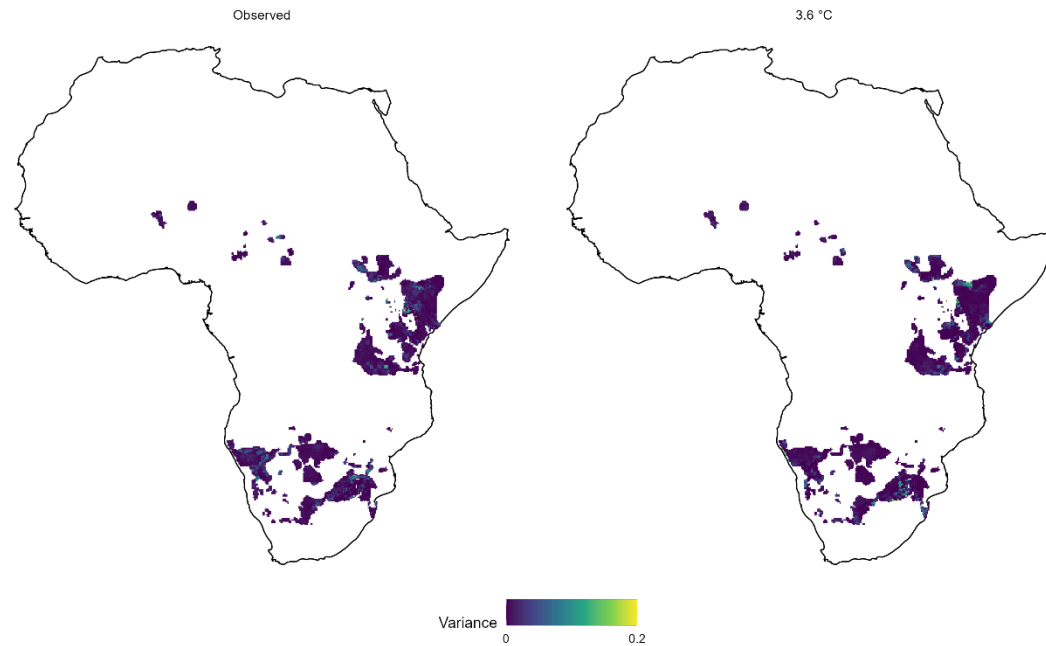


Figure S5.1: The variance in each cell from 1000 differently weighted Zonation runs in the weight sensitivity analysis, for the Observed period and the 3.6°C global warming scenario.

Zonation outputs with no input layer for lion climate suitability

When lion climate suitability is not included as an input layer in the zonation analyses, a majority of areas retain a similar priority ranking to when it is included (Figure S5.2; Figure S5.3). Across the full range of all giraffe, 90% of the area maintains a priority rank of between -0.03 and +0.03 from the priority rank with a lion input layer, and 98% of the area remains within -0.06 and +0.12 of the original priority rank. The largest difference in ranking is in the south-west portion of the Reticulated giraffe's range (Figure S5.3), which gains rank when the lion input layer is removed.

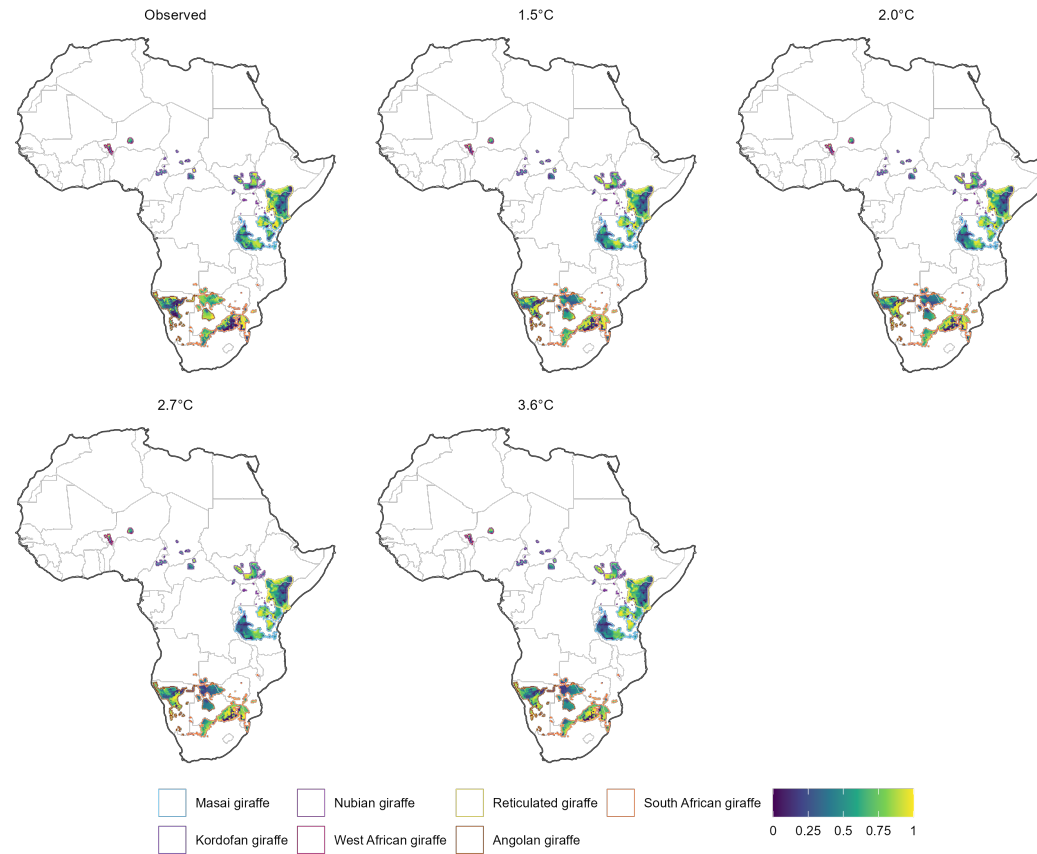


Figure S5.2: Zonation priority rank outputs for each species and subspecies when lion input layers are removed from the analyses. Panels show outputs under observed climate and warming levels of 1.5, 2.0, 2.7, and 3.6°C.

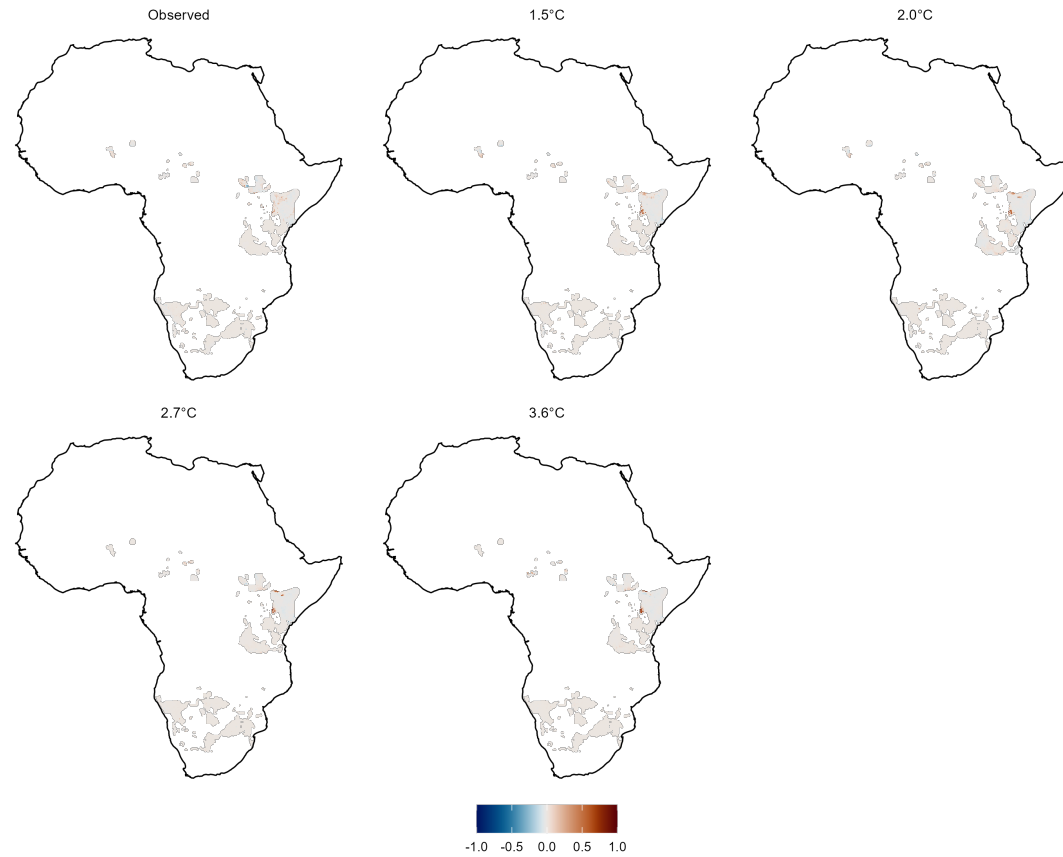


Figure S5.3: change in Zonation conservation priority across Africa after removal of lions, shown for observed climate and four warming scenarios. Colours represent the difference in priority rank value between models without lions and the main model, with red colours indicating increased priority and blue colours indicating decreased priority following lion removal. Panels show outputs under observed climate and warming levels of 1.5, 2.0, 2.7, and 3.6°C.

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GiraffeClim: A Web-Based Tool for

Exploring Climate Change

Impacts on Giraffe

Abstract

The impact of research largely depends on how accessible it is to users. Even with the increase in open access publications and the dissemination of research through social media and other channels, research is often published in a way which does not maximise its accessibility. With this in mind, an application has been developed to host the outputs of this thesis. GiraffeClim is an intuitive, free-to-access, and publicly available web-based application. It houses projections of climate suitability for each giraffe species at various global warming levels, highlights areas of conservation priority at these warming levels, and displays reports on the projected climate changes within each giraffe population's geographic range. The intended users are the Giraffe Conservation Foundation, protected area managers, national wildlife authorities, and other conservation practitioners involved in giraffe conservation. It is hoped that by maximising the accessibility of the data produced in this thesis, GiraffeClim will support evidence-based, and climate change-informed conservation planning and decision-making for giraffe across Africa.

6.1 Introduction

Research outputs relevant to conservation are most impactful when they are easily accessible to practitioners and policymakers. Bridging the gap between conservation

research and practice has long been a topic of discussion (Sunderland *et al.*, 2009; Fuller *et al.*, 2014; Kadykalo *et al.*, 2021). Many conservation practitioners operate outside of academia and are often unable to access peer-reviewed literature due to publisher paywalls. Even where open-access publishing has increased, research outputs are frequently communicated through static text and figures, which can limit their interpretability and practical usefulness for decision-making.

Reflecting growing recognition of these challenges, the widespread adoption of the FAIR (Findability, Accessibility, Interoperability, and Reusability) guiding principles over the last decade highlights a broader push to improve the accessibility and reuse of scientific outputs beyond academia (Wilkinson *et al.*, 2016). In parallel, there has been a rapid expansion of web-based tools and repositories designed to facilitate open access to datasets, models, and analytical outputs, allowing users to explore complex information interactively rather than through static summaries.

Within conservation science, web-based tools have been used to support stakeholder engagement in conservation planning (e.g. Babbar-Sebens *et al.*, 2015), inform policy and land-use decision-making (e.g. Grêt-Regamey *et al.*, 2017), enable interactive data visualisation and analysis (e.g. Bandi *et al.*, 2022; Han *et al.*, 2024), and increase the accessibility of spatial prioritisation outputs for conservation interventions (e.g. Kipkemboi *et al.*, 2023). A recurring theme across the literature is that these tools are most effective when they are designed with a clear understanding of the end user; those which are overly technical and poorly aligned with practitioner needs are unlikely to influence conservation outcomes (Rose *et al.*, 2017). Similarly, Griffith (2025) stated that these tools can come with inherent limitations surrounding the knowledge needed to fully understand and utilise the data, and the danger of data being used without a clear understanding of its limitations. The author did, however, highlight three web-based applications that have successfully enabled conservation organisations to access land-use data that would otherwise have been unavailable, facilitating conservation actions and decision making (Griffith, 2025). One widely cited example of a user-friendly, accessible conservation tool is Conservation Evidence (Sutherland *et al.*, 2019) – a freely accessible database that synthesises scientific evidence on the effectiveness of conservation actions. By presenting research outputs in a clear, structured, interactive, and openly available format, tools such

as this demonstrate how accessibility can enhance the uptake of evidence-based conservation.

Inspired by such tools, and to maximise usefulness, core outputs of this thesis have been packaged into a web-based application for easy exploration of the potential impact of climate change on giraffe. This application, GiraffeClim, is hosted online with shinyapps.io (Posit Software, PBC, 2025) and is free to access. The primary user of the application is expected to be the Giraffe Conservation Foundation (GCF), which is a science-led conservation organisation. GCF were consulted during the design phase of the application to ensure that features were relevant and to highlight any potentially useful additional features. Whilst the application is primarily aimed towards those with a good working knowledge of scientific principles and climate-change concepts, more detailed descriptions of data are nonetheless provided to aid users who may be less familiar with certain methodologies, data, and terminology.

The application is currently available at:

<https://ellie-rose-harris.shinyapps.io/Giraffe-CC/>

6.2 Methods

The application was made using the *shiny* package (Chang *et al.*, 2022) in R 4.2.2 (R Core Team, 2022). R packages used to construct key elements in each of the pages include *leaflet* (Cheng *et al.*, 2024), *NestedMenu* (Laurent, 2022), and *leaflet.extras2* (Sebastian, 2025). For information on individual data layers contained within the application, please refer to the previous thesis Chapters 3, 4, and 5. Some data available to users in the application are not outputs of this thesis, but rather data that was used in the Zonation analysis in Chapter 5. This data is hosted on the application with appropriate permissions where necessary and is compliant with the appropriate data usage rights: global human modification index of terrestrial ecosystems (Kennedy *et al.*, 2020), human population SSP2 projections and base year (Jones and O'Neill, 2016, 2020; Gao, 2020), and maximum consecutive months (MCM) of drought and waterlogging (Price *et al.*, 2022).

6.3 Overview of the application

The GiraffeClim application has a 'Home' page, four additional pages grouping data by functional output, and a 'Data Information' page. This structure was designed so that users can easily navigate to the data output most relevant for their task. The application opens on the 'Home' page, which gives the user an overview of the data available in each of the other pages (Figure 6.1). The four data pages are: 'Climate Suitability', 'Priority Conservation Areas', 'Data Comparison', and 'Species Range Profiles'. The 'Climate Suitability' page is a full-screen interactive map which enables users to identify areas of suitable climate for each species of giraffe and at multiple levels of global warming. The 'Priority Conservation Areas' page integrates further information on extreme climate, biotic interactions, and anthropogenic impacts, presenting a priority ranking where higher scores indicate areas of greatest conservation importance. The next page, 'Data Comparison', allows users to visualise two datasets side-by-side, making it easier to compare climate suitability and conservation priority data, as well as other conservation-relevant data. The final data page is 'Species Range Profiles', which displays reports on the observed and projected climate changes within giraffe species' geographic ranges, as an insight into the population's exposure to climate change. Finally, users can navigate to the 'Data Sources' page to find detailed descriptions and sources for the data housed within the application. The following sections detail the main tabs and provide a succinct 'how to' guide for potential users.

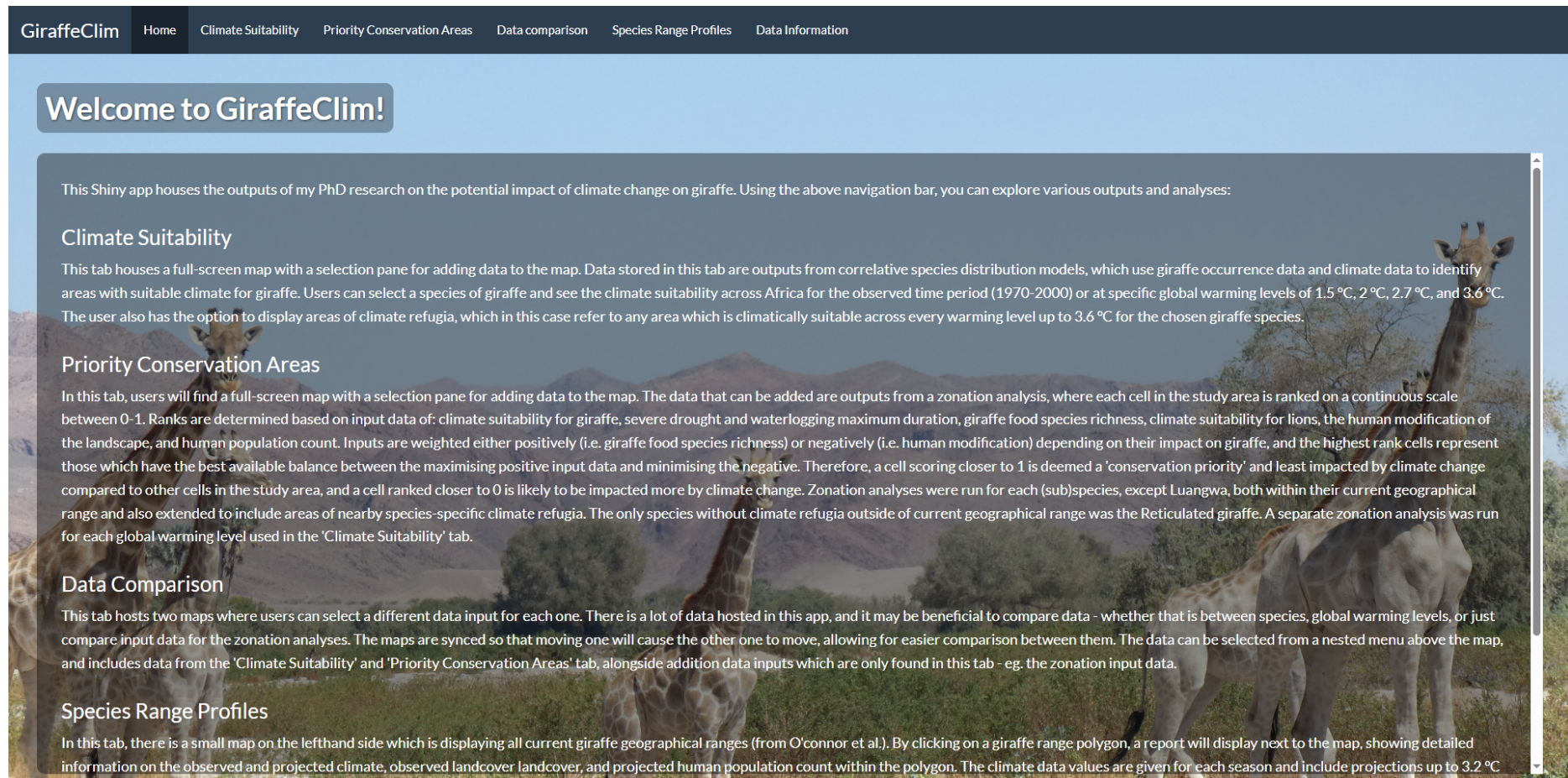


Figure 6.1: The opening 'Home' page of GiraffeClim, where users are introduced to the different tabs that are accessible from the navigation pane at the top of the screen.

6.3.1 Climate Suitability

Page set-up: A full screen, interactive map displays layers depending on the user's selection from an input panel on the lefthand side.

Purpose: To enable users to explore areas of suitable climate for each giraffe species, for observed and projected global warming levels.

The interactive map allows users to examine the climate suitability in greater detail by zooming in or changing the focal point to examine different areas. Additionally, the SDM layers in GiraffeClim are shown across the entire extent of Africa, whilst in Chapter 4 they were cropped to a 300 km buffer area surrounding the species' geographic range. Users can view either climate suitability at individual warming levels or climate refugia which is suitable for the species across all warming levels explored. This gives conservation practitioners the flexibility to examine specific warming levels and use their own judgement for what to consider in present-day decision-making.

How to use:

1. Species selection: Choose a giraffe species from the list
2. Output type: Select either 'Climate Refugia' or 'Individual warming level'.
 - a. If 'Individual warming level' is selected, a further selection option appears where the user can choose from Observed, 1.5°C, 2°C, 2.7°C, 3.6°C.
3. Render the map by clicking 'Go', remove layers by clicking 'Clear'.
4. Additional options:
 - a. Toggle the species' current range map on or off
 - b. Download a .png file of the displayed map

For example, to view areas of climate refugia for Masai giraffe, the user would select 'Masai' and then 'Climate refugia' for Output type (Figure 6.2)

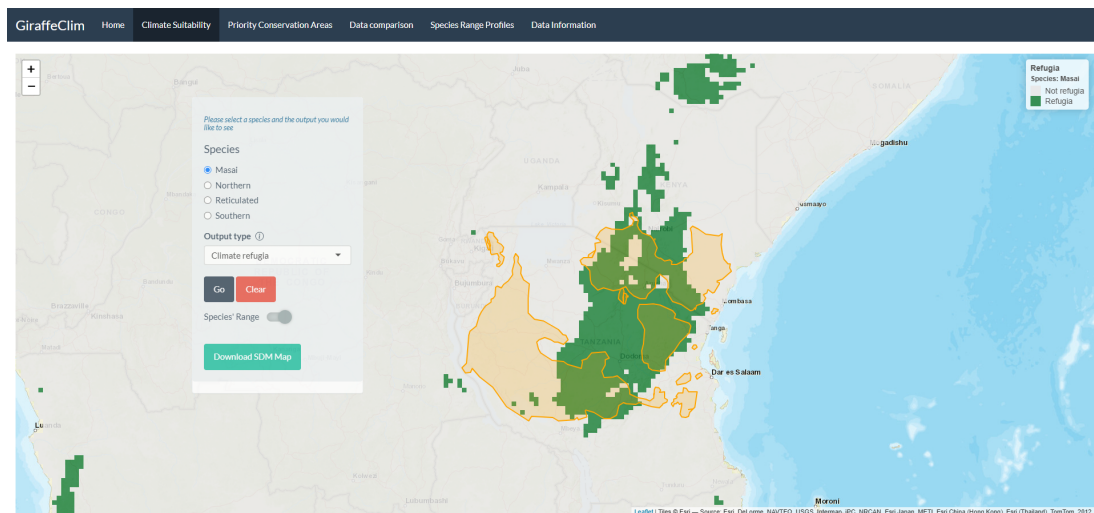


Figure 6.2: The Climate Suitability page of GiraffeClim. The map is displaying areas of climate refugia (green) for Masai giraffe, with the species' range added to the map (orange). Areas which are not suitable appear grey. The lefthand input menu shows the selection of 'Masai', 'Climate refugia' and 'Species' range' which were selected to bring up this input.

Useful features:

Table 6.1: Useful design features found on the 'Climate Suitability' page of GiraffeClim

Item	Feature	Purpose and description
Map input menu	Draggable	Enhances map visibility by allowing users to reposition the input panel, preventing it from obscuring key map features.
	Semi-transparent	Improves visual focus on the map. When the user's mouse is not hovering over the panel, it fades slightly to reduce visual clutter, while remaining visible.
	Tooltip for 'Output type'	An information icon provides contextual help. When hovered over, it displays a description of the available output options.

Item	Feature	Purpose and description
Download button	PNG export	Enables users to download a high-resolution image of the current map view, facilitating its use in reports, presentations, or sharing with stakeholders.

6.3.2 Priority Conservation Areas

Page set-up: A full screen, interactive map displays layers depending on the user's selection from an input panel on the lefthand side.

Purpose: To enable users to explore the conservation priority rankings and ecological stability of areas within and near species' current geographic range, for observed and projected global warming levels.

In Chapter 5, conservation priority rank maps are shown for each of the species and subspecies, with a clear description of which areas have ranked highest or lowest. This page of GiraffeClim can display the conservation priority rank maps for each species, with the added benefit of displaying the underlying input data values to give context to the rankings.

How to use:

1. Species selection: Choose a giraffe species or subspecies (where applicable) from the list.
2. Analysis type: Select either 'Individual warming level' or 'Ecological Stability'.
 - a. If 'Individual warming level' is selected, two further input options appear – 'Select warming level' where the user can choose from Observed, 1.5°C, 2°C, 2.7°C, 3.6°C, and 'Select extent' with a choice of 'Species' geographic range' or 'Include nearby refugia'.
3. Render the map by clicking 'Go', remove layers by clicking 'Clear'.
4. Additional options:

- Toggle the species' current range map on or off
- Click anywhere on the map where data is displayed to see the values of inputs into the Zonation analysis (e.g. Acacia species richness value)
- Download a .png file of the displayed map

For example, to get the output shown in Figure 6.3, which is the conservation priority rankings for Masai giraffe and areas of nearby climate refugia at 2°C of warming, the user would select the following inputs:

- Species/subspecies: 'Masai'
- Select analysis: Individual Warming Level
- Select Warming Level: 2°C
- Select extent: Include nearby refugia

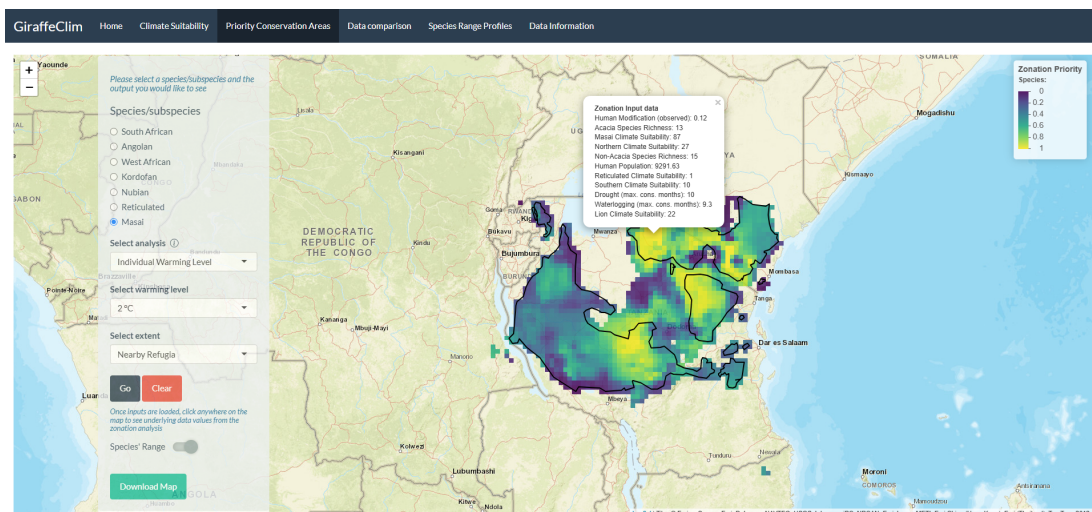


Figure 6.3: The 'Priority Conservation Areas' page of GiraffeClim, with data showing for the core Zonation analysis for Masai giraffe at 2°C and extended to areas of nearby climate refugia for the species. The Masai geographic range is shown as a black outline and the yellow cells area areas of highest priority compared to dark blue cells which have the lowest priority rank. The white box shows values from the Zonation analysis input data for the clicked cell, allowing users an insight into why cells are ranked high/low. The information icon next to 'Select analysis' on the input menu is a tooltip which, when hovered over, displays additional information to the user about the selection they are making.

Useful features:

Table 6.2: Useful design features found on the ‘Priority Conservation Areas’ page of GiraffeClim

Item	Feature	Purpose and description
Map input menu	Draggable	Enhances map visibility by allowing users to reposition the input panel, preventing it from obscuring key map features.
	Semi-transparent	Improves visual focus on the map. When the user’s mouse is not hovering over the panel, it fades slightly to reduce visual clutter, while remaining visible.
	Tooltip for ‘Select analysis’	An information icon provides contextual help. When hovered over, it displays a description of the analysis types available to select.
Popup	Data display	When the user clicks on a map cell, a popup appears showing data values for the input variables used in the displayed Zonation analysis.
Download button	PNG export	Enables users to download a high-resolution image of the current map view, facilitating its use in reports, presentations, or sharing with stakeholders.

6.3.3 Data Comparison page

Page set-up: The screen is split into two interactive maps, with an input pane at the top of the page where users can select inputs for each map from a nested menu.

Purpose: To enable users to easily compare data for different warming levels or compare individual data for the same warming level (for example, MCM of drought compared to

human population).

The benefit of this page for conservation practitioners is the ability to directly compare the same impact at different warming levels, or two different impacts for the same warming level (for example, duration of drought and climate suitability for giraffe at 2°C). The pop-up on the Zonation page is useful for understanding data inputs for specific cells to understand their priority rank value, but the Data Comparison page enables users to display the actual underlying data for the full extent of Africa. For easier data comparison, the two maps are synchronized so that changing the zoom level or the view on one map will be mirrored on the other. There is also a mirrored mouse icon which duplicates the location of the mouse from one map to the other.

How to use:

1. Choose Left Map data: Click the 'Left Map' button at the top of the screen to bring up a nested menu. The menu is organised by warming level and subsequent options will appear when your mouse hovers over an entry with nested items.
2. Choose Right Map data: Repeat the above step using the 'Right Map' button.
3. Additional options:
 - a. Add or remove the range of any (sub)species on the map by using the top right menu in each map.
 - b. Click anywhere on the map where data is displayed to see the value of the displayed data layer
 - c. Download a .png file of the combined maps

For example, to compare climate suitability for Masai giraffe at observed climate and 2°C warming as shown in Figure 6.4, users should do the following:

- Left Map: Select 'Observed', then 'Masai', then 'Climate suitability'
- Right Map: Select '2°C', then 'Masai', then 'Climate suitability'
- On both maps: select 'Masai range' to display the range

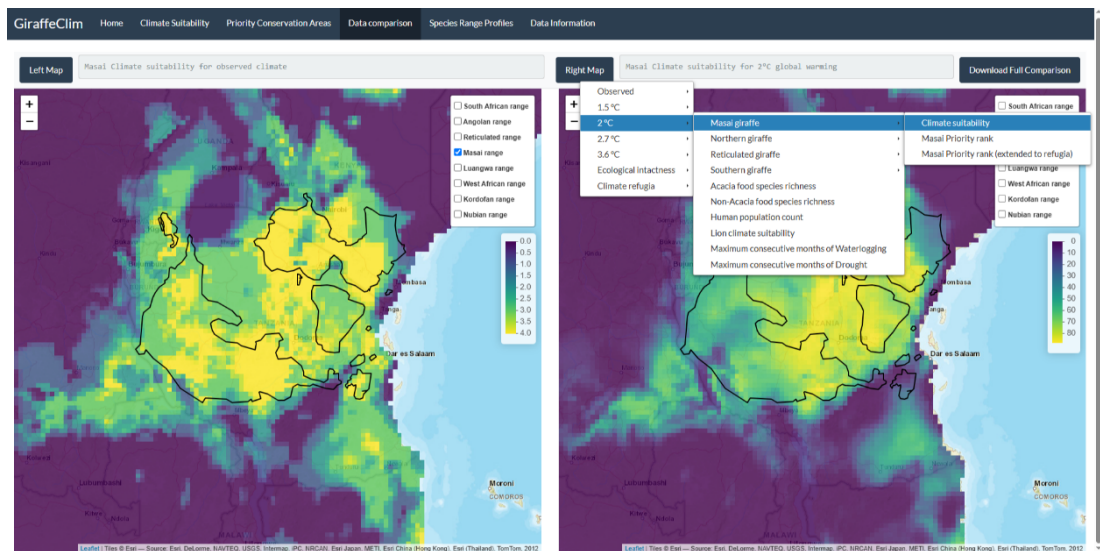


Figure 6.4: The Data Comparison page of GiraffeClim, showing two adjacent interactive maps. In this example, the lefthand map shows observed climate suitability for Masai giraffe and the righthand map shows Masai climate suitability at 2°C global warming. For both maps, yellow shows higher climate suitability. Users select data by using the ‘Left Map’/‘Right Map’ buttons, which open up a nested menu when clicked, as can be seen on the righthand map. The maps are synced so that viewpoints and zoom levels are identical when the maps are moved, allowing for easier comparison of data.

Useful features:

Table 6.3: Useful design features found on the ‘Data Comparison’ page of GiraffeClim

Item	Feature	Purpose and description
Nested menu	Structured layer selection	Provides a compact, organised way to browse and select data layers. This improves navigation and helps users easily find the data they wish to visualise.
Side-by-side maps	Mirrored cursor marker	Synchronises the mouse location across both maps, enabling precise visual comparison of specific locations.
	Synced viewpoint and zoom level	Panning or zooming on one map is mirrored on the other, ensuring both maps stay aligned for easy side-by-side comparison.
Popup	Data display	Clicking on a map cell opens a popup showing the value of the data in that cell.

Item	Feature	Purpose and description
Download button	PNG export	Enables users to download a high-resolution image of the current map view, facilitating its use in reports, presentations, or sharing with stakeholders.

6.3.4 Species Range Profiles

Page set-up: A small interactive map on the lefthand side which displays all of the giraffe species' geographic ranges. Selecting a species' range polygon brings up the associated range report on the righthand side of the map. The user can change between 'Climate', 'Drought and Waterlogging', 'Land Use', and 'Population' data.

Purpose: The purpose of this page is to make the giraffe range reports generated in Chapter 3 accessible to conservation practitioners.

These reports are important to include alongside the climate suitability and priority conservation area outputs because they give an alternative guide to the potential exposure of giraffe to climate change. Reports were generated for over 100 giraffe ranges – a quantity which is not feasible to include in the original thesis chapter.

How to use:

1. Click one of the species' ranges on the map.
2. Explore the report using the headings on the left (see Figure 6.5).

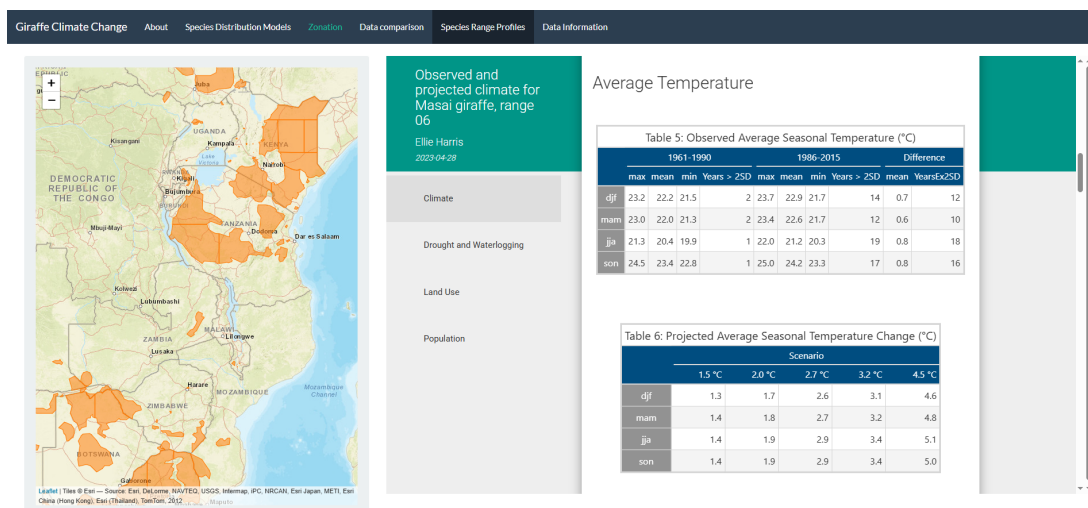


Figure 6.5: An example output of the ‘Species Range Profiles’ page of GiraffeClim, showing how the report is displayed when a range polygon is clicked. Each range report shows climate, land use, and human population data as an average across the selected polygon.

Useful features:

Table 6.4: Useful design features found on the ‘Species Range Profiles’ page of GiraffeClim

Item	Feature	Purpose and description
Linked map and range reports	Range selection	Improves interpretability by visually linking the report content to the relevant geographic range on the map, helping users clearly identify the area being referred to.

6.3.5 Data information

Page set-up: A full-screen table which contains each data layer, the value range for that data, and a description of the data.

Purpose: To give users more detailed information on each of the data layers and aid in any clarifications needed to understand the data.

Useful features:

Table 6.5: Useful design features found on the ‘Data Information’ page of GiraffeClim

Item	Feature	Purpose and description
Information table	Row highlight	When the user hovers their mouse over a row in the table, it is highlighted, improving readability and helping users focus on specific information.

6.4 Summary and Future Directions

GiraffeClim provides a freely accessible, web-based platform to explore climate suitability and conservation priorities for each giraffe species under multiple global warming scenarios. By integrating species-specific outputs with interactive maps and summary reports, the application facilitates evidence-based conservation planning and allows practitioners to identify areas of climate refugia and conservation priorities.

Despite its utility, the application has some limitations. In part, these limitations reflect the uncertainties and assumptions in the underlying data, which are discussed in each of the relevant chapters. Another key limitation of GiraffeClim is that its outputs rely on correct user interpretation. Whilst the application is designed to be intuitive and user-friendly, the accuracy and usefulness of insights depend on users’ understanding of the assumptions, uncertainties, and constraints of SDM and Zonation outputs. Misinterpretation of model projections or priority scores could lead to overconfidence in the results or misinformed conservation decisions. However, given that the primary user of the application is the science-led organisation – the Giraffe Conservation Foundation (GCF) – and that the ‘Home’ and ‘Data information’ pages provide context to the analyses and data, the risk of misinterpretation is somewhat mitigated.

In the future, development of the application will be guided by user feedback. Potential improvements include the addition of external data layers (permission-dependent), such as

land cover or protected area boundaries, which aid in conservation decision-making. Other useful features may be the addition of a user feedback page to streamline communication or features enabling users to add their own data layers to the maps. These enhancements would expand the long-term functionality of the application but were outside the scope of this thesis, which focused on hosting the outputs generated in each chapter. Early feedback from GCF has been entirely positive and highlighted the usefulness of packaging research outputs into a user-friendly application. Overall, GiraffeClim demonstrates how web-based tools can improve accessibility and usability of conservation research outputs, bridging the gap between academic analyses and practical decision-making.

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Conservation Implications, Limitations, and Conclusions

7.1 Introduction

The decline of giraffe populations by 36-40% between 1985 and 2015 has been a large cause of concern for the future of the species (Muller *et al.*, 2018). However, thanks to the conservation actions of national wildlife authorities, conservation organisations, and local people, some populations have begun to recover (Brown *et al.*, 2021). As of 2020, Masai, Luangwa, and West African giraffe had increasing populations in all of the countries they are found in, whilst other (sub)species had mixed population trends depending on the country (Brown *et al.*, 2021). Current and future impacts of climate change are still a threat, especially given the geographic range contraction and fragmentation seen in many giraffe populations over recent decades (Muller *et al.*, 2018). To ensure the greatest chance of long-term success in the face of climatic and anthropogenic threats, conservation actions must be evidence-based and climate change-informed. This thesis has therefore aimed to build on the existing knowledge base in understanding the exposure to and potential impact of climate change on each of the four giraffe species and their subspecies. Understanding that future climate changes will not happen in isolation from concurrent anthropogenic impacts, the research in this thesis has integrated multiple climatic and anthropogenic factors to identify which areas should be a priority for the conservation of each giraffe species and subspecies.

7.2 General findings

In Chapter 3, the exposure of each species and subspecies to projected changes in climate was examined. Differences between (sub)species' observed climate were established and areas which would be exposed to novel climate conditions under future warming scenarios were quantified. Then, in Chapter 4, statistical species distribution models were built to project changes to suitable climate for each giraffe species. Areas which remained climatically suitable for a given giraffe species under all warming levels were deemed climate refugia. Finally, priority conservation areas were identified by using Zonation software to find areas with the best available balance of food resources and suitable climate compared to climatic, biotic, and anthropogenic threats. The key findings from each chapter are listed below:

Chapter 3 – The (dis)similarity of climate within the geographic ranges of each giraffe species and subspecies suggests possible differences in climatic niches. This highlighted the importance of species-specific climate suitability projections in subsequent chapters. Results showed that all species and subspecies are projected to see increases in seasonal average minimum and maximum temperature, but the direction of change in precipitation varied. The percentage of (sub)species' current geographic range exposed to novel climate at 2°C and 3.2°C was greatest for Northern giraffe using the climate envelope approach.

Chapter 4 – Shifts in areas of suitable climate are projected at every warming level and for each species. However, at least 24% of each species' current geographic range retains suitable climate at warming levels up to 3.6°C. These areas of species-specific climate refugia are key for a least-regrets strategy for conservation, given the uncertainty surrounding future global warming levels.

Chapter 5 – Priority areas for giraffe conservation shift depending on the projected warming level, but all species and subspecies have areas which are ranked as a top 10% priority across all global warming levels. West African giraffe are the only (sub)species where none of the top priority areas are in a protected area.

7.2.1 Broad conservation implications across climatic suitability scenarios

The combined results from Chapters 3–5 indicate that, across the range of giraffe, projections of suitable climate fall under four broad scenarios, each associated with distinct conservation implications.

1. **Currently climatically suitable and projected to remain suitable:** These areas represent the core of long-term persistence for giraffe populations. In these areas, conservation actions should prioritise the maintenance of existing habitat quality and quantity, limiting non-climatic threats such as habitat conversion, poaching and barriers to movement, and preventing further fragmentation. Where these areas do not fall within protected areas, they could be nominated for protected area status, or may need more intense monitoring and community engagement to help mitigate any anthropogenic threats.
2. **Currently suitable but projected to become unsuitable:** These areas present a different challenge. Conservation actions may depend on the level of warming at which the area is projected to become unsuitable, and the uncertainty that conservationists are willing to take on. If it is only projected to become unsuitable at the highest levels of warming, conservation actions may be somewhat similar to the above if conservationists accept a level of threat regarding increasing global warming levels. For those projected to become unsuitable under lower warming scenarios, conservation effort could focus on adaptation options within the range area, for example, maintaining or increasing heterogeneity and microclimatic refuges. However, in these instances, long-term sustainability may be unrealistic, and conservation actions may instead look to facilitate the movement of these populations to more robust areas of climatic suitability.
3. **Currently unsuitable but projected to become suitable:** These areas may represent potential future range expansion zones. Although these areas often fall outside the present giraffe range and are therefore not traditionally prioritised, the ability of giraffe to move long distances suggests they may become increasingly important under climate change. These areas are unlikely to support immediate conservation investment but are relevant for forward-looking planning. Conservation

implications include identifying and maintaining movement corridors, avoiding future land-use changes that could create barriers to dispersal, and, in exceptional cases, evaluating the feasibility and risks of assisted colonisation if natural movement is constrained.

4. **Currently unsuitable and projected to remain unsuitable:** These areas are unlikely to contribute substantially to giraffe conservation under climate change. In these areas, conservation actions for giraffe are likely to be limited to establishing whether they can act as movement corridors between suitable range areas in order to facilitate movement across a broader geographic range.

The four scenarios outlined above summarise the main ways in which climate suitability may change for giraffe. The following section presents the species- and subspecies-specific results in more detail, with reference to these scenarios where appropriate.

7.3 Species-specific findings and conservation implications

In this section, the projected climate change impacts for each giraffe species and subspecies are synthesised, drawing on outputs from across the previous research chapters. Using the newly developed GiraffeClim application for visualisation, each (sub)species is introduced with a brief overview of its current conservation status and geographic distribution, followed by a detailed summary of projected climate change impacts and priority conservation areas. This chapter adds to the outputs of previous chapters by interpreting findings in the context of publicly available giraffe conservation action plans, to highlight relevant conservation implications. Given the coarse spatial resolution of the analyses in this thesis, the suggestions and recommendations made here are intended to provide broad-scale insights that can complement the finer-scale, site-specific knowledge of the Giraffe Conservation Foundation (GCF) and other conservation practitioners. Together, these insights aim to support the integration of climate change considerations into future giraffe conservation planning.

7.3.1 Southern giraffe

Southern giraffe (*Giraffa giraffa*) have the largest population of all four giraffe species – at approximately 49,850 individuals (Brown *et al.*, 2021), and they are expected to be listed as least concern in the next IUCN red list assessment, expected in 2025 (Giraffe Conservation Foundation, 2024, accessed 27.04.2025). Excluding some extralimital populations (those found outside of their natural geographic range), Southern giraffe are currently found in South Africa, Zimbabwe, Botswana, Zambia, Angola, Eswatini, Mozambique, Namibia, and Malawi. The Angolan subspecies is only found in Namibia and Botswana, but the South African subspecies is found in all of these countries.

South African giraffe

South African giraffe (*G. g. giraffa*) experienced an increasing population in recent decades and population numbers are higher than for other species or subspecies (Brown *et al.*, 2021).

South African giraffe are projected to be exposed to increases in seasonal average maximum and minimum temperature, and reduced precipitation across all seasons and warming levels (see Chapter 3). Alongside this, there is projected to be an increase in the maximum consecutive months (MCM) of severe drought. By 2°C of global warming, using the average across 21 CMIP5 GCMs, 55% of the South African giraffe's geographic range is projected to exceed the seasonal average temperature and precipitation limits that the subspecies currently experiences.

The SDMs presented in Chapter 4 show that overall climate suitability declines in the northern part of the South African giraffe's geographic range, with suitable climate shifting polewards at increasing global warming levels. This is the same pattern found when historical occurrence records were included in the models. The main models project that at 1.5°C, populations most at risk are those in Botswana and Malawi, and from 2°C global warming, populations in Zambia, Angola, Mozambique, Namibia, and Zimbabwe start to lose large areas of climate suitability. The only areas of internal climate refugia (areas of suitable climate for Southern giraffe at all warming levels and within the current geographic range of South African giraffe) are in South Africa, Zimbabwe, and a small area in Mozambique near the South African border in Limpopo National Park (see Chapter 4, Figure 4.8). Countries where there are no areas of climate refugia for Southern giraffe are

Botswana, Zambia, Namibia, and Malawi. This is consistent with the refugia projected in the sensitivity models that incorporate historical occurrence records.

Across all projected global warming levels, the areas of lowest conservation priority rank within the South African giraffe's geographic range (see Chapter 5, section 5.3.6) are near Harare and Bulawayo in Zimbabwe; in Malawi; in the Z F Mgcawu district in the Northern Cape of South Africa; and near Johannesburg and within the Limpopo province of South Africa. The fragmented geographic ranges in the Northern Cape likely have a low rank because of the higher projected MCM of drought, and lower food species richness (for both Acacia and non-Acacia species) compared to other South African geographic range (see Figure 7.1). Examining the 'ecological stability' analysis input data shows that this area also has the biggest percentage increase in drought MCM compared to the rest of the geographic range at global warming levels of 3.6°C. The other low-ranking areas in South Africa (in and near the Limpopo province) are likely ranked low due to the higher levels of human modification of land (gHM) in these areas (Figure 7.2).

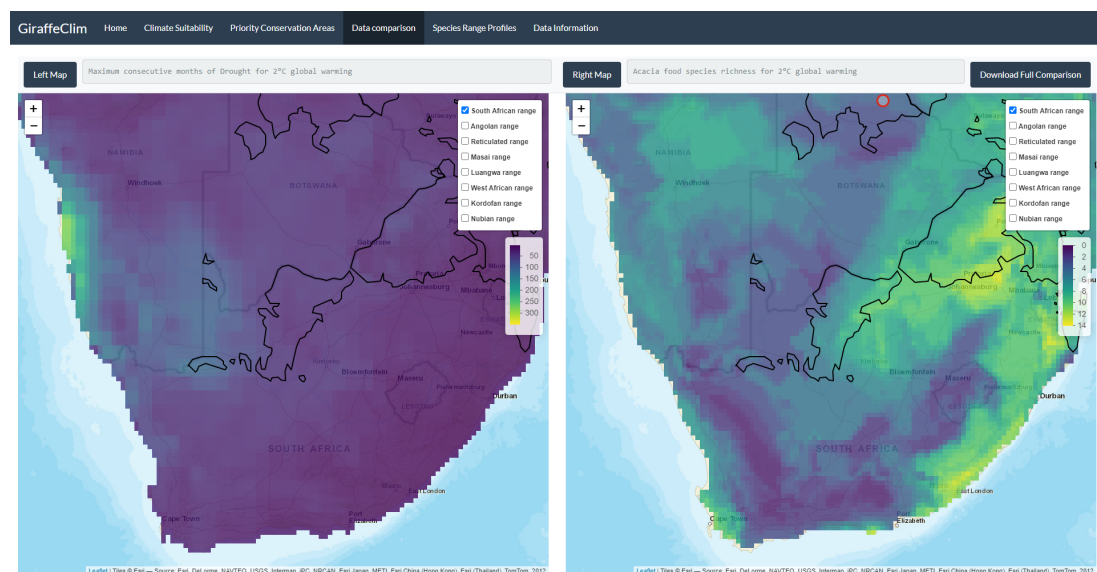


Figure 7.1: A screenshot of the GiraffeClim application on the 'Data Comparison' page showing MCM drought (left) and Acacia species richness (right) at 2°C of warming. For both maps yellow is a higher value and blue is a lower value.

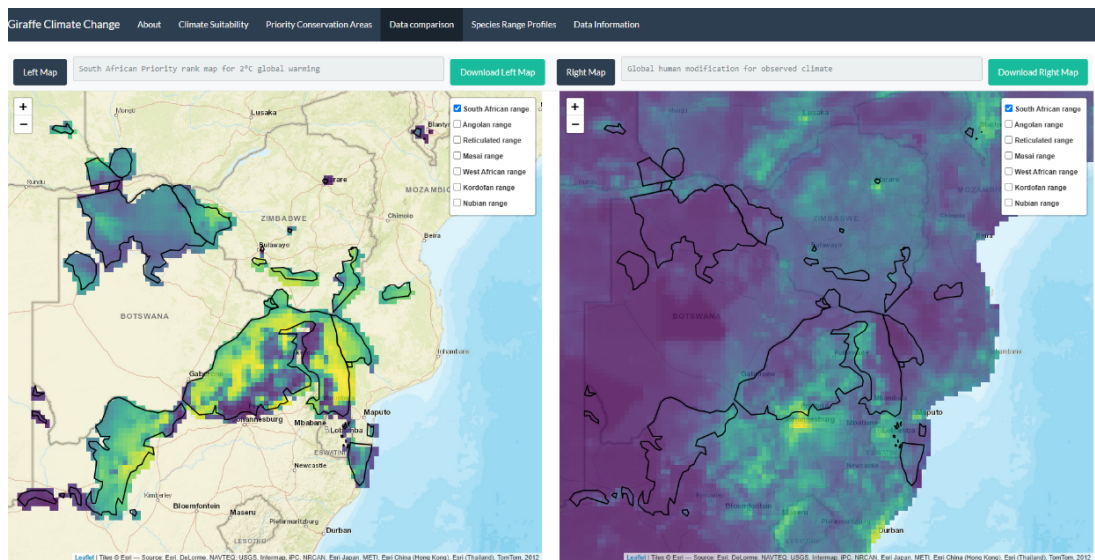


Figure 7.2: A screenshot of the GiraffeClim application showing the Data Comparison tab with the 2°C priority rank map for South African giraffe (left map) and gHM layer (right)

The Botswanan and adjacent Namibian, Angolan, and Zambian ranges for South African giraffe do not rank the lowest, but they never have a high rank. These geographic ranges are projected to have low climate suitability for Southern giraffe, and relatively low Acacia and non-Acacia food species richness compared to the rest of the subspecies' geographic range.

Conservation Implications

Areas of key importance for conserving South African giraffe under increasing global warming levels are Kruger National Park and many private game reserves across South Africa. Areas of concern – those ranked poorly in the Zonation analysis – are found in Botswana, Zambia, Zimbabwe, Malawi, Eswatini and Mozambique. GCF and their partners have produced two publicly available conservation action plans which cover South African giraffe – one for the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA), and one for Malawi. In addition, population translocations are being conducted in Mozambique. The KAZA TFCA conservation action plan, which is relevant to both subspecies of Southern giraffe, is discussed later, under Angolan giraffe conservation implications.

The Malawi Giraffe Conservation Action Plan, 2024-2028 (DNPW, 2023) highlights habitat loss, disease, snaring, and climate change as key threats to giraffe in the country. A key aim in this conservation action plan is to increase giraffe distribution within Malawi, and one of

the activities listed in the report is: ‘Conduct a reintroduction assessment for all potential restoration sites, including aspects of habitat (e.g. food availability), threats (e.g. disease), management effectiveness, financial resources, security, and monitoring infrastructure.’ Unfortunately, there are no areas of climate refugia for Southern giraffe in Malawi, and even at 1.5°C global warming, climate suitability for these geographic range areas is low. Despite this being an area of concern, it should be noted that factors such as topography can increase climate suitability at a finer spatial scale. Nonetheless, it will be important to have effective monitoring in place to understand whether giraffe populations are being impacted by the change in climate suitability. The Zonation input data provided in the ‘Data comparison’ tab of the GiraffeClim application has not been clipped to the geographic ranges of giraffe and could be used to examine additional projected climate change impacts in potential reintroduction sites across Malawi. The main population of giraffe in Malawi are found in Majete Wildlife Reserve, which is projected to see a threefold increase in drought MCM from the observed period to 2°C warming (Figure 7.3). Drought adaptation measures, such as installing artificial waterholes, may therefore be an important conservation action for this population.

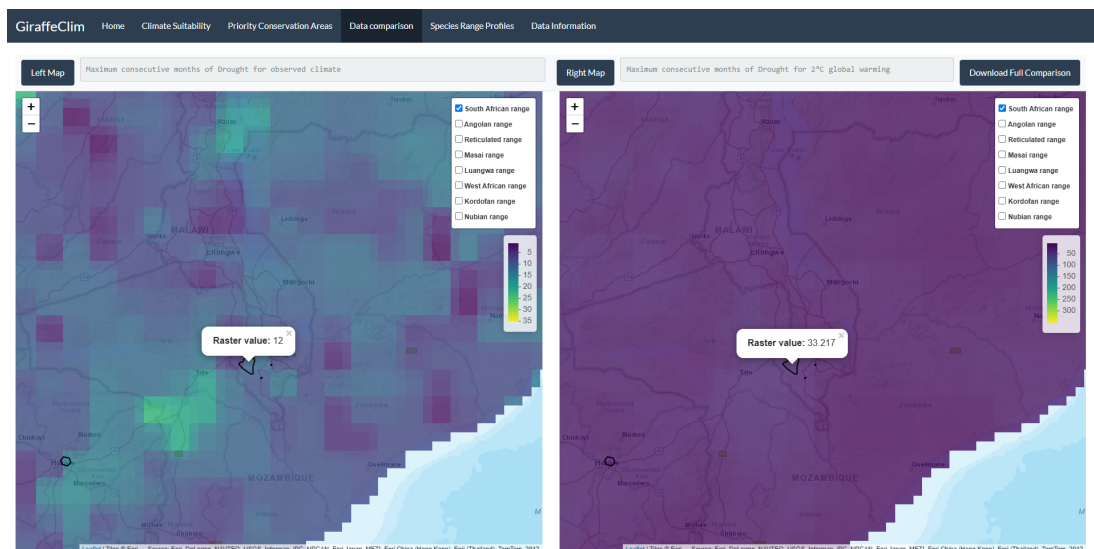


Figure 7.3: A screenshot from the GiraffeClim application, showing the MCM of drought in the observed climate period compared to 2°C warming (right). The popup shows a value of 12 on the left map and a value of ~33 on the righthand map. Both maps are centred on Malawi.

Translocations of South African giraffe into Mozambique in the last few years have been carried out in an effort to bolster giraffe populations in the country. Giraffe populations

faced large declines during the Mozambican civil war from 1977-1992, and for a prolonged period of time after the war, due to high poaching levels and weak law enforcement (Roque *et al.*, 2022). A GCF translocation report documents the translocation of 12 South African giraffe to the Karingani Game Reserve in August of 2023 (Giraffe Conservation Foundation, 2023). The GiraffeClim application shows that the Karingani Game Reserve is not only an area of climate refugia for Southern giraffe, but that it ranks in the top 20% priority rank for South African giraffe at all warming levels (Figure 7.4). This information highlights the importance of bolstering the population in this area and can help support conservation practitioners when gaining appropriate approvals and permits for these conservation actions.

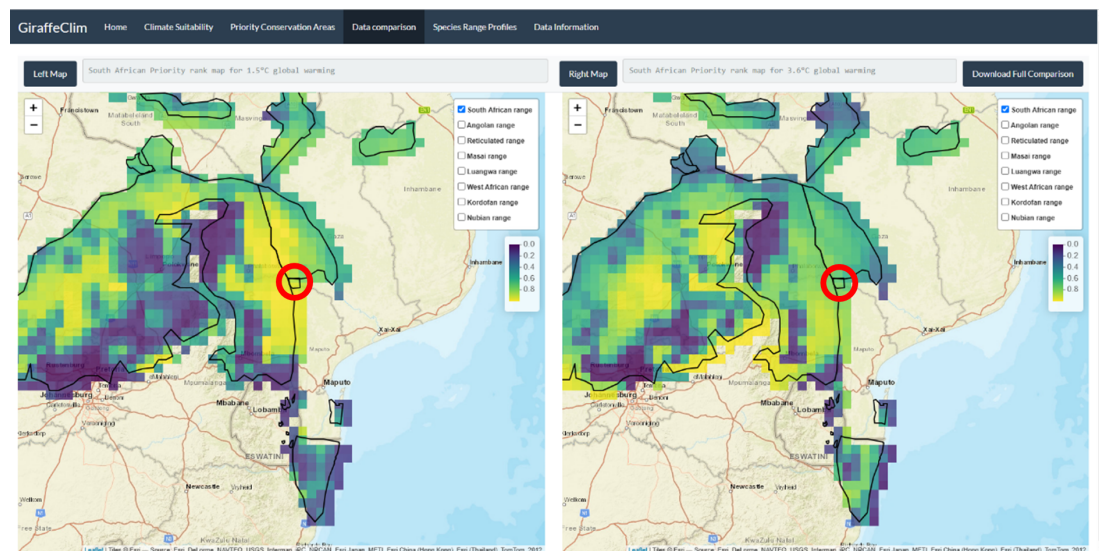


Figure 7.4: The priority rank maps for South African giraffe at 1.5 and 3.6°C global warming, centred on the Karingani Game Reserve in Mozambique (red circle).

Angolan giraffe

Angolan giraffe (*G. g. angolensis*) are classed as ‘Least Threatened’ in the current IUCN red list assessment (Muller *et al.*, 2018). This subspecies has increased from an estimated population of less than 10,000 several decades ago to more than 20,000 today (Brown *et al.*, 2021).

Projected climate changes across the current geographic range of Angolan giraffe include increases of seasonal average maximum temperature greater than that projected for other species and subspecies. Seasonal average minimum temperature is projected to increase, and seasonal average precipitation is projected to decrease across all seasons and warming

levels. The severe drought MCM is projected to increase across all warming levels, and at a higher level than all other species/subspecies. At 2°C global warming, over 50% of the Angolan giraffe's current geographic range is projected to experience novel climate conditions.

The species distribution models for Southern giraffe project that at 1.5°C global warming, most of the current Angolan giraffe range in Namibia and Botswana retains suitable climate. However, at 2°C, the Angolan giraffe range in Botswana (in the Kalahari and Khutse Game Reserves) and some of the most eastern ranges in Namibia are projected to lose climate suitability (Figure 7.5). At this warming level, climate suitability reduces in the northwest of Namibia but the range area in central Namibia remains highly suitable. The historical occurrence SDMs found a similar pattern at 2°C warming, but less severe, and projected a smaller area would lose its climate suitability in Botswana, and most of the range in Namibia would retain climate suitability until 2.7°C. Most of the climate refugia in Angolan giraffe range is towards central and southern Namibia, but pockets of refugia can be found in the northwest part of their range. The historical SDMs showed this same pattern, with only a minor increase in internal climate refugia in the central Angolan giraffe range in Namibia.

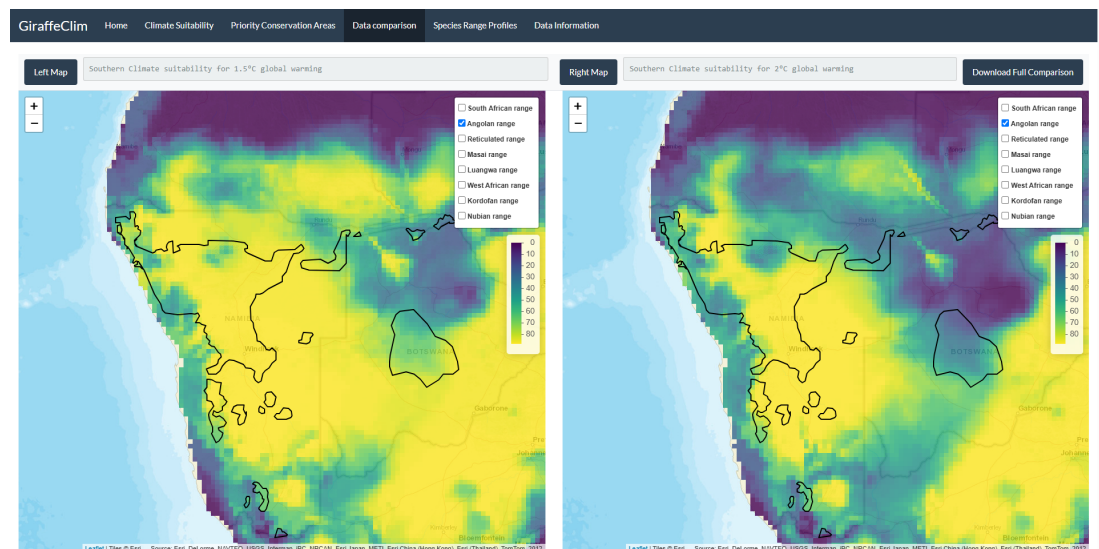


Figure 7.5: A comparison of climate suitability for Southern giraffe at 1.5°C (left) and 2°C (right). The Angolan giraffe range is also shown (black outline).

The Zonation outputs highlight that Angolan giraffe range areas in central Namibia are less impacted by climatic and non-climatic threats across all global warming levels. The fragmented ranges in southern and eastern Namibia are ranked lowest and are potentially

at the most risk under the climate change scenarios explored. Using GiraffeClim to examine these areas shows that MCM drought is projected to be higher in these areas compared to the rest of the Angolan giraffe range at all levels of global warming (Figure 7.6). Given that gHM is relatively low across the entire Angolan giraffe range (except near the Namibian capital, Windhoek), it is likely the higher levels of drought driving these low rankings. The range areas in southern Namibia are projected to have the highest Acacia and non-Acacia food species richness at global warming levels of 2.7°C and above, and may therefore be important for giraffe conservation at higher global warming levels. Adaptation measures such as artificial waterholes may be a useful strategy to sustain giraffe populations here under future climate change.

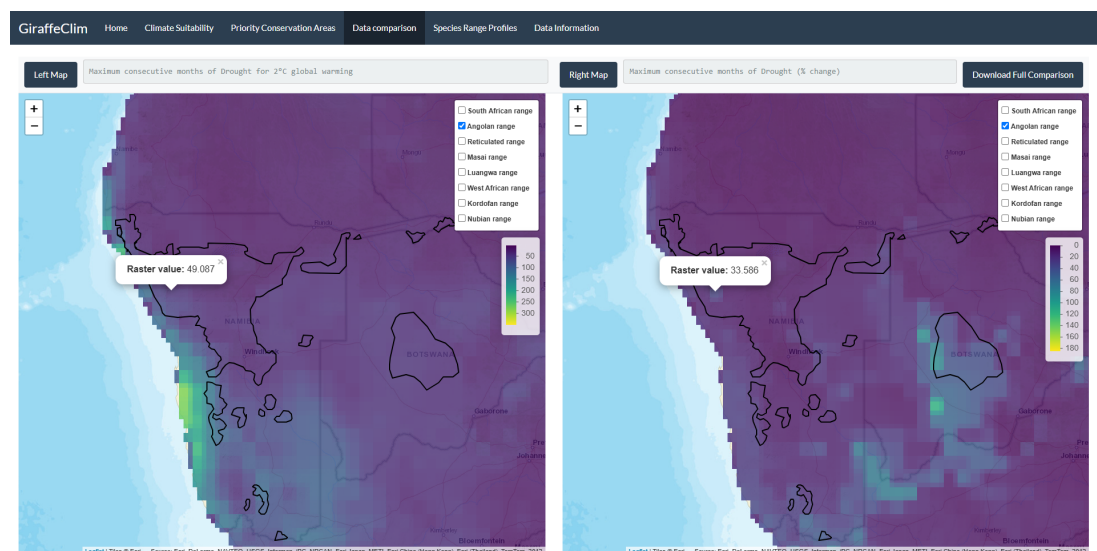


Figure 7.6: The maximum consecutive months of drought projected at 2°C (left) and the percentage change in maximum consecutive months of drought at 3.6°C compared to observed climate (right)

Conservation Implications

For Angolan giraffe, unprotected land north of the Namibian capital, Windhoek and community conservancies in northeast Namibia are important conservation areas under climate change. Angolan giraffe are most at risk from the impacts of climate change in the Botswanan ranges and the fragmented southern and eastern Namibian ranges.

There is currently one publicly available conservation action plan that covers the Angolan giraffe range, created by GCF and their partners: the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) conservation action plan. This plan also covers parts of

South African giraffe range and so is discussed in the context of both subspecies below.

The KAZA TFCA (Figure 7.7) encompasses areas of South African and Angolan giraffe range in Angola, Botswana, Namibia, Zambia, and Zimbabwe. The GCF – KAZA TFCA Giraffe Conservation Strategy for 2022-2026 (Giraffe Conservation Foundation, 2022) lists several key conservation actions for the area: identifying and addressing gaps in knowledge with targeted studies and streamlined data sharing, facilitating landscape level connectivity, promoting community engagement and local livelihoods, and supporting law enforcement. The KAZA-TFCA does not have any areas of climate refugia (those that are climatically suitable for giraffe up to 3.6°C global warming) for Southern giraffe, and is an area of concern for both subspecies.

KAZA TFCA

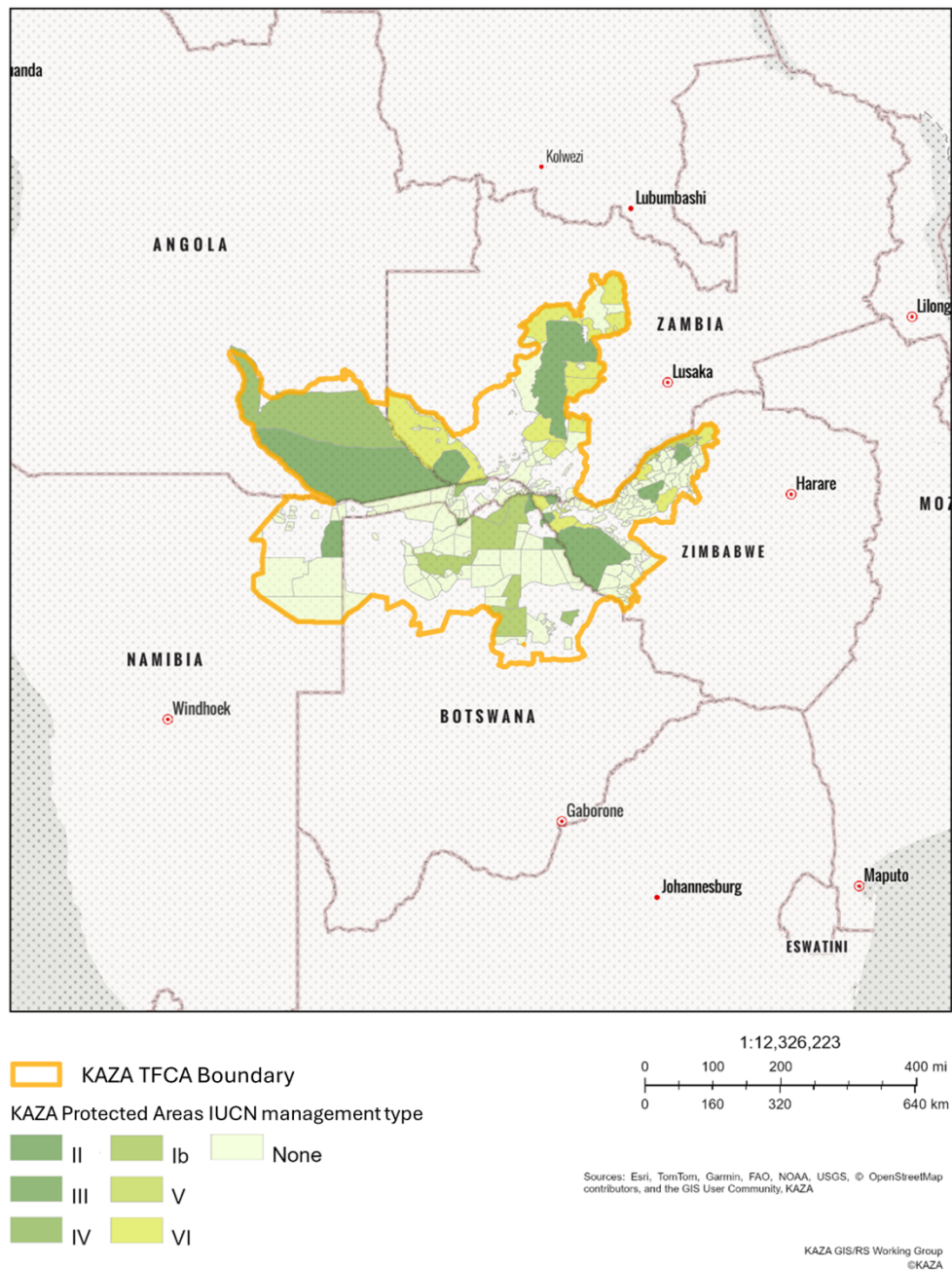


Figure 7.7: The Kavango Zambezi Transfrontier Conservation Area (KAZA TFCA; orange boundary). Protected areas within the conservation area are shown, coloured corresponding to their IUCN management type. Figure downloaded from <https://www.kavangozambezi.org/maps/> for 'Land cover and protection' (KAZA TFCA, accessed 18.04.2025)

The GCF – KAZA TFCA conservation action plan highlights climate change as a threat to this area, particularly given the decrease in giraffe numbers during the 20-year drought in Botswana in the 1980s. The poleward shift in suitable climate for Southern giraffe, and

projections of increasing MCM of severe drought (Price *et al.*, 2022) show that higher levels of global warming pose a threat across the KAZA TFCA. Even at projections of 1.5°C global warming, climate suitability for Southern giraffe greatly diminishes in the Botswanan part of KAZA-TFCA. The Moremi Wildlife Park in Botswana and adjacent areas to the northwest (both within the Okavango Delta), are the only areas which retain suitable climate for Southern giraffe up to 2°C global warming. This, and areas of suitable climate in the surrounding countries within KAZA-TFCA should be considered a high priority for giraffe conservation. Ensuring adequate wildlife corridors is likely to be an important conservation tool here to allow giraffe to track suitable climate into these areas.

Many of the areas within KAZA TFCA rank poorly for Angolan and South African giraffe at all projected warming levels. Within KAZA TFCA, the areas which have the highest priority ranking are in the Hwange National Park in Zimbabwe, the Okavango Delta in Botswana, and the Luengue-Luiana National Park in Angola. However, priority rankings should be interpreted carefully in this region for several reasons. Firstly, the priority rank maps only show which areas are most/least at risk from climate change impacts compared to the entire species/subspecies geographic range. Because only a small portion of each subspecies geographic range is found in KAZA TFCA, the priority rankings are less relevant and instead the scores should only be interpreted in relation to which areas within the KAZA-TFCA broadly score higher or lower. Secondly, the conservation area contains two subspecies, meaning that there are two separate rank maps which do not relate to each other. This means that a low-ranking area for Angolan giraffe could potentially represent an area that would have ranked highly for Southern giraffe, making interpretability across the entire area difficult. The KAZA TFCA conservation action plan applies to a spatially explicit area, where the aim is to support giraffe populations in-situ. With this in mind, examining Zonation data inputs (for example, projections of food species richness or duration of extreme events) will be most useful and can inform which areas may be most in need of adaptation measures, effective management, and increases in landscape connectivity.

Using the GiraffeClim application, it is clear that within the Botswanan portion of KAZA-TFCA, the Okavango delta is a key area for giraffe conservation. At 2°C global warming, it is projected to have the highest non-Acacia food species richness and some of

the lowest MCM of severe drought compared to surrounding areas (Figure 7.8). In addition, Acacia food species richness is projected to be higher than surrounding areas under the same levels of warming, and the previously mentioned relatively high climate suitability makes it a potential stronghold for giraffe if global warming can be limited to 2°C.

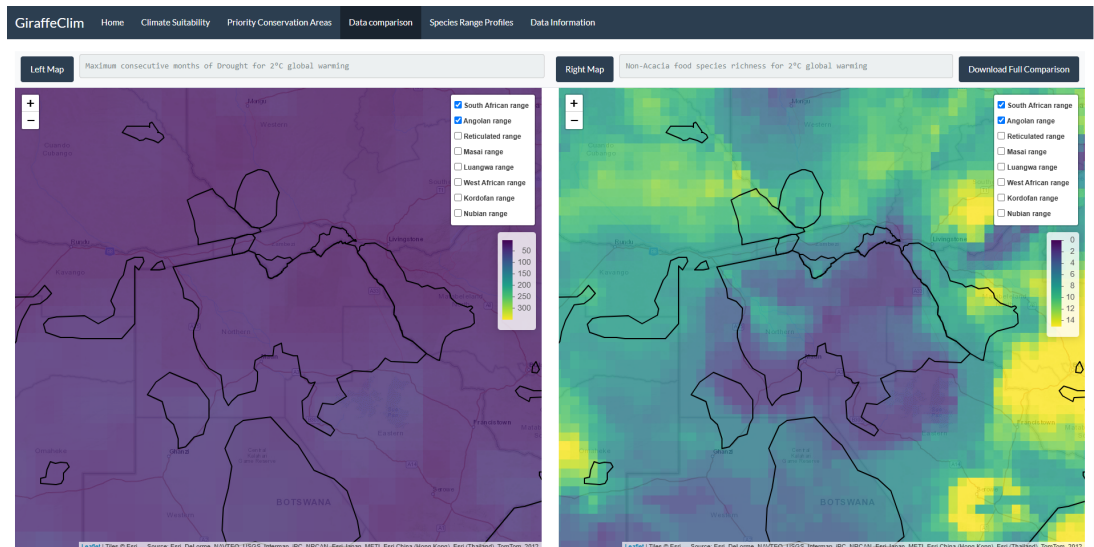


Figure 7.8: The MCM of drought (left) and non-Acacia food species richness (right) at 2°C, centred on the KAZA TFCA and showing polygons of Angolan and South African giraffe range. On both maps, higher values are shown in yellow, and lower values are shown in dark blue.

For both subspecies of Southern giraffe, worsening drought is likely to be one of the largest impacts from climate change and measures to increase available water, for example, artificial waterholes, are likely to be an important adaptation measure.

7.3.2 Masai giraffe

Masai giraffe (*Giraffa tippelskirchi*), consisting of the Masai and Luangwa subspecies, are found in Kenya, Tanzania, Zambia and Rwanda and have a population of ~45,000, giving them the second largest species population after Southern giraffe (Brown *et al.*, 2021). As of 2020, Masai giraffe populations in all four of these countries were increasing (Brown *et al.*, 2021). In the upcoming IUCN assessment, Masai giraffe are expected to be listed as Endangered (Giraffe Conservation Foundation, 2024, accessed 27.04.2025).

Masai giraffe

Masai giraffe (*G. t. tippelskirchi*) are listed as Endangered under the most recent IUCN red list assessment (Muller *et al.*, 2018). They are found in southern Kenya, Tanzania, and in Akagera National Park in Rwanda.

Climate projections from Chapter 3 show that Masai giraffe are projected to see increases in seasonal average maximum and minimum temperature, with increases in seasonal average precipitation in the December-February (tail end of the short rainy season in Tanzania) and March-May (long rain season in Tanzania). In the June-August (dry season) and September-November (end of dry season, start of short rains) seasons, rainfall is projected to decrease across the geographic range at increasing warming levels. Across the Masai giraffe geographic range, longer MCM of severe drought are projected compared to waterlogging (see Chapter 3, section 3.3.2). Only 15% and 39% of the Masai giraffe's range is exposed to novel climate conditions at 2°C and 3.6°C global warming, respectively. This is much smaller than for all other species/subspecies.

The climate suitability models highlighted large areas in the eastern portion of the Masai range which are suitable across all examined global warming levels. This is also supported by the historical sensitivity analysis, which projected a highly similar area of internal refugia. Both analyses showed worsening climate suitability for Masai giraffe in the western portion of their range at increasing warming levels, except the sensitivity analyses projected slightly higher loss of climate suitability. Akagera National Park is projected to have suitable climate by over half of the GCM-SDM models at 2°C, but at higher warming levels, it is projected to have low climate suitability. Many of the Protected Areas (PAs) in western Tanzania have low climate suitability at higher warming levels, and limiting global warming to 2°C would retain climate suitability across most of the Masai giraffe geographic range (Figure 7.9).

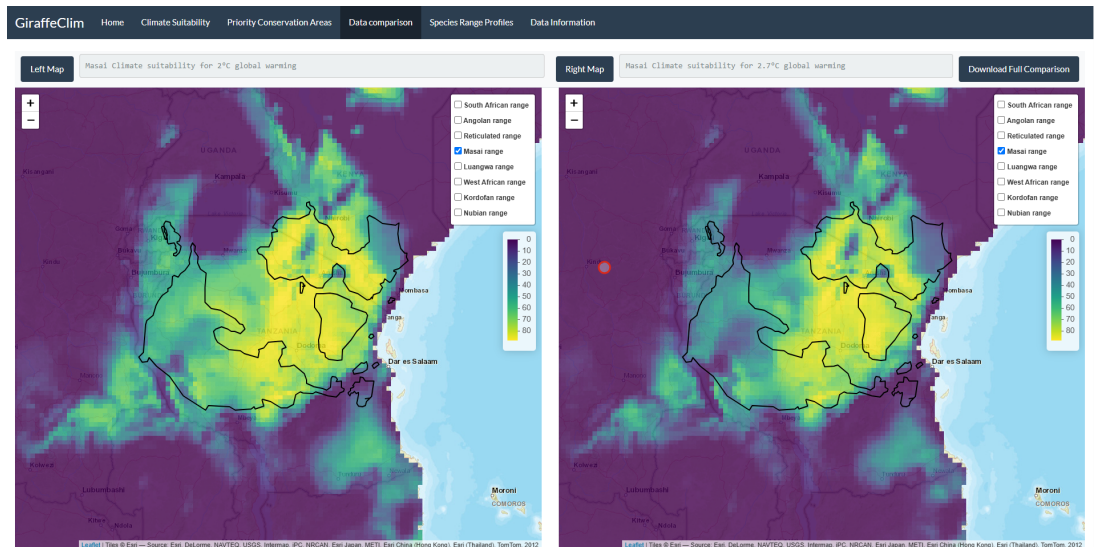


Figure 7.9: Climate suitability for Masai giraffe at 2°C (left) and 2.7°C (right). The red circle on the righthand map is the mirrored mouse cursor – a useful feature of the GiraffeClim application to make comparisons between maps easier

The Zonation outputs for Masai giraffe highlight similar areas to the climate suitability maps as being least impacted by climate change. The Manyara and Arusha regions and the Ruaha National Park (NP) in Tanzania rank highly across all warming levels. Generally, areas on and around the Kenyan-Tanzanian border rank highly across warming levels. The Tsavo West NP in Kenya ranks very highly and has a higher rank than the Tsavo East NP. Examining the Zonation input data in the GiraffeClim application shows that this is likely due to the much lower levels of *Acacia* species richness projected in Tsavo East compared to Tsavo West (Figure 7.10). There is also slightly lower climate suitability projected for giraffe in Tsavo East NP at all warming levels. All other input data in these regions is very similar.

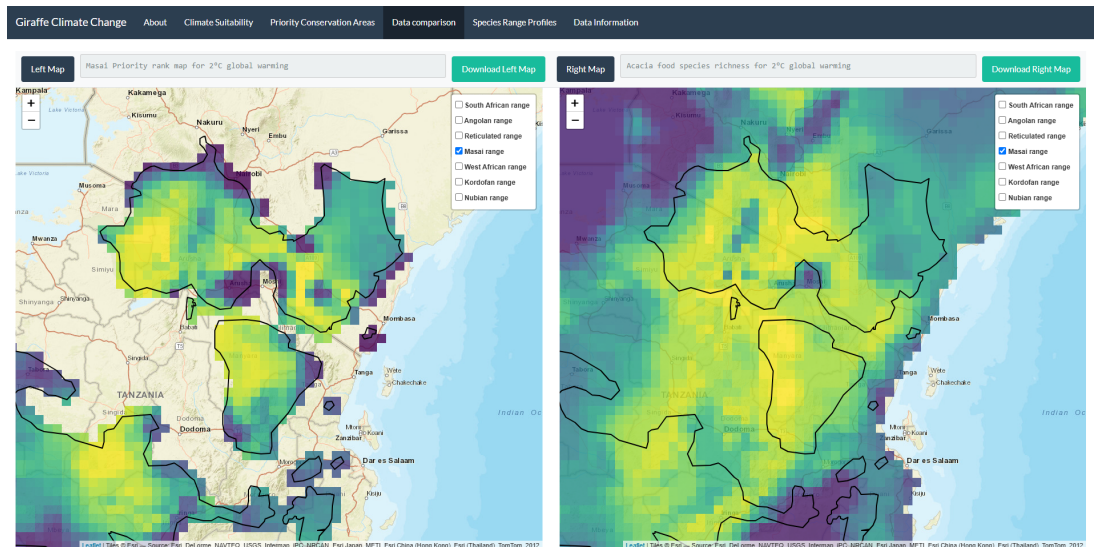


Figure 7.10: The priority rank map for Masai giraffe (left) and Acacia species richness (right) at 2°C global warming.

There is a large area of climate refugia outside the Masai giraffe's current range which could be important under higher levels of climate change. However, in the Zonation analyses, much of this area had a low ranking, likely due to the high levels of gHM in these areas. These areas could therefore be targeted for habitat restoration, improving their potential to support giraffe populations at multiple levels of global warming.

Conservation Implications

Conservation plans exist for Masai giraffe ranges in Tanzania, Rwanda, and Kenya.

The Tanzania Wildlife Research Institute (TAWIRI) has produced a National Giraffe Conservation Action Plan, which was developed in 2019 for the years 2020-2024 (TAWIRI, 2019). The report highlights land-use changes as one of the main threats to giraffe in Tanzania, specifically in the context of climate change where species need unimpeded movement to track suitable climate. Following from this, one of the strategic objectives was to 'Maintain, protect and restore Giraffe habitats and connectivity between giraffe populations', with relevant activities to facilitate pilot restoration of degraded giraffe habitats, migratory routes, corridors and dispersal areas. The formation of corridors is likely to be especially important in areas of western Tanzania because of the lower climate suitability for Masai giraffe at increasing global warming levels. As can be seen using the GiraffeClim application, there is a large area of external climate refugia for Masai giraffe

extending between Masai ranges in western Tanzania and northeastern Tanzania (Figure 7.11). Increased protection of these areas, and targeted habitat restoration where necessary could therefore be an effective conservation tool for Masai giraffe, facilitating range shifts to track suitable climate. Indeed, when viewed in conjunction with the gHM data, it is clear that human modification of terrestrial systems is high in these areas – potentially impeding giraffe movement (Figure 7.11). The Tanzania Ministry of Natural Resources and Tourism (MNRT) has identified important wildlife corridors in this region and note in the ‘Tanzania Wildlife Corridors Assessment, Prioritization, and Action Plan’ (MNRT, 2022) that some may need restoration to maintain effectiveness. As such, one of the action points is: ‘Restore habitat converted to cropland or excessively intensive grazing areas to provide minimum corridor width for wildlife movement’. If effectively conserved and restored, these corridors could facilitate movement to areas of climate refugia for Masai giraffe.

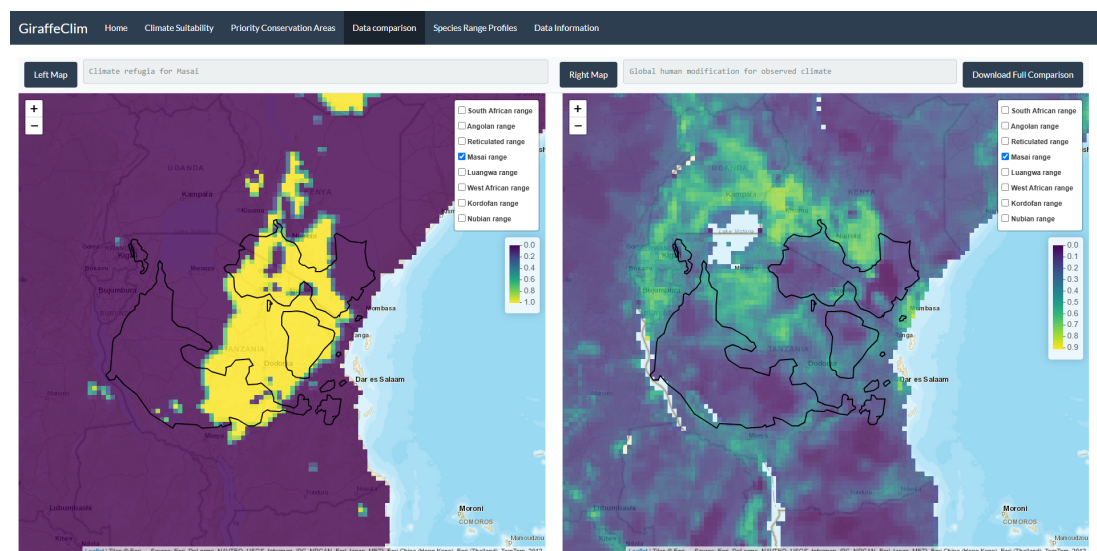


Figure 7.11: Areas of climate refugia for Masai giraffe (left - yellow) and gHM (right) where yellow indicated a higher proportion of the land has been modified, and blue a lower proportion

The conservation action plan for giraffe in Kenya (2023-2027) mentions the identification of potential conservation areas as well as threat hotspots as key activities (Kenya Wildlife Service (KWS), 2023). The Zonation analyses in this thesis identified areas of Masai giraffe range in Kenya which are closest to the Tanzanian border as priority conservation areas for the species. In particular, Tsavo West NP is considered a high conservation priority and is ranked higher than Tsavo East NP. This puts increased weight on the importance of Tsavo West NP as a key conservation area for Masai giraffe, and mirrors findings by Muthiuru *et*

al. (2024) who also found that Tsavo West NP had increased fine-scale habitat suitability compared to Tsavo East NP. Using GiraffeClim to examine potential threats shows that most of the Masai giraffe range in Kenya is projected to retain a large proportion of observed Acacia species richness (SR) up to 3.6°C warming. Tsavo East NP retains less Acacia SR and is also projected to have longer MCM of drought at higher levels of global warming (Figure 7.12).

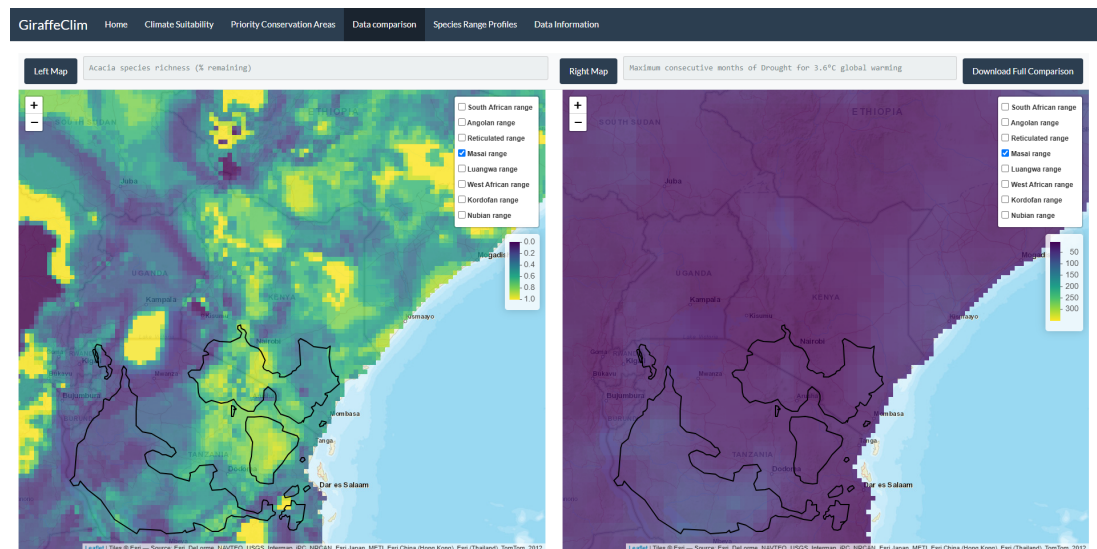


Figure 7.12: A screenshot of the GiraffeClim application and Data Comparison page with two maps centred on Kenya and Masai giraffe range shown in a black outline. The lefthand map shows Acacia species richness remaining at 3.6°C warming compared to observed levels, and the righthand map shows the MCM of drought at 3.6°C warming.

The African Parks Network and GCF have produced a giraffe conservation action plan for Akagera NP in Rwanda, for 2024-2029 (African Parks Network, 2023). The report shows that in 2022 and 2023, the northern areas of the park had the highest giraffe population density, and up to 2°C global warming, these areas are projected to remain climatically suitable for Masai giraffe. With increasing levels of warming, these areas are projected to become less climatically suitable, as less than half of the models project suitable climate. Climate change is explicitly mentioned in the action plan as a potential, but ‘unknown’ threat to giraffe, stating that shifts in flood patterns or vegetation communities could impact available giraffe habitat. Looking at the Ecological Stability inputs, Akagera National Park is projected to have negligible percentage increases and decreases in waterlogging at 3.6°C warming compared to present (Figure 7.13). This does not necessarily correspond to flooding, which is difficult to project, but is a good indication of the water balance given

the combination of precipitation and temperature. In addition to this, examining projections of climate suitability for food species shows a projected decrease in species richness at 2°C global warming. Non-Acacia food species richness across Akagera NP is projected to decrease from 15 species in the observed climate period to at least 10 species at 1.5 and 2°C, dropping to 9 species at 2.7°C global warming. Similarly, Akagera NP is projected to have suitable climate for 10 Acacia species until 2°C where the climate is projected to be suitable for 9 species. Given research showing that the majority of giraffe's diet consists of less than 10 key species (Pellew, 1984; Furstenburg and van Hoven, 1994; Deacon and Smit, 2017), these food species richness levels may remain sufficient for giraffe. Considering this, and projections of suitable climate for giraffe, if global warming levels are limited to no greater than 2°C, Akagera NP may remain a suitable area for giraffe.

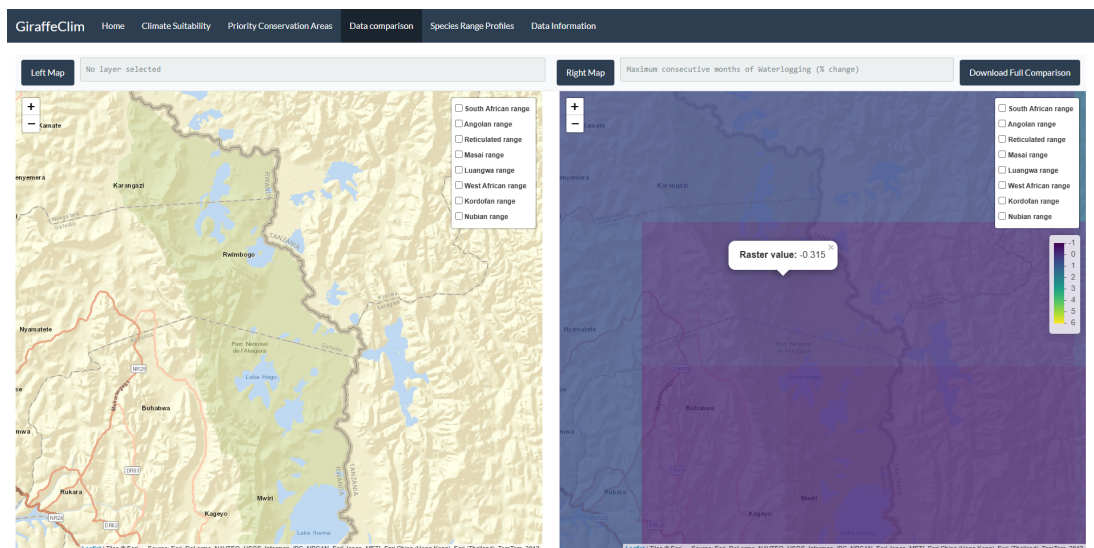


Figure 7.13: Akagera National Park (left - green area) shown as a reference point and (right) the projected percentage change in MCM of severe waterlogging at 3.6°C compared to observed. This screenshot was taken from the 'Data Comparison' tab of the GiraffeClim application.

Luangwa giraffe

The taxonomic status of the Luangwa giraffe (*G. t. thornicrofti*) has been uncertain (Fennessy *et al.*, 2016), but research now suggests it should be treated as a separate subspecies of Masai giraffe (Coimbra *et al.*, 2021). Population estimates put it at 650 individuals, found only in Zambia (Brown *et al.*, 2021) and it is categorised as vulnerable in the IUCN red list (Bercovitch *et al.*, 2018).

Given that the Luangwa giraffe was excluded from the analyses in Chapter 3 and 4 due to

limited data and small geographic range size, the information on this subspecies is limited to giraffe range reports and an examination of Zonation input datasets shown in the GiraffeClim application.

The range report for Luangwa giraffe shows a projected increase in average, maximum, and minimum seasonal average temperature at roughly the same rate as global warming levels (i.e. increases of 1.4 - 1.6°C across all seasons at 1.5°C global warming). Precipitation is projected to decrease across all seasons and warming levels by up to ~3 mm at 1.5°C and 4 mm at 2°C global warming. The largest decrease in seasonal average precipitation is projected occur in the September – November (hot and dry) season, which has an observed seasonal average precipitation of 20.8 mm as a median across the subspecies’ geographic range. MCM of severe drought (SPEI12 -1.5) as an average across the subspecies’ geographic range, is projected to increase from seven months in the observed climate period to 17 months at 1.5°C, 26 months at 2°C, and increasing with every further 0.5°C increase in global warming (Figure 7.14).

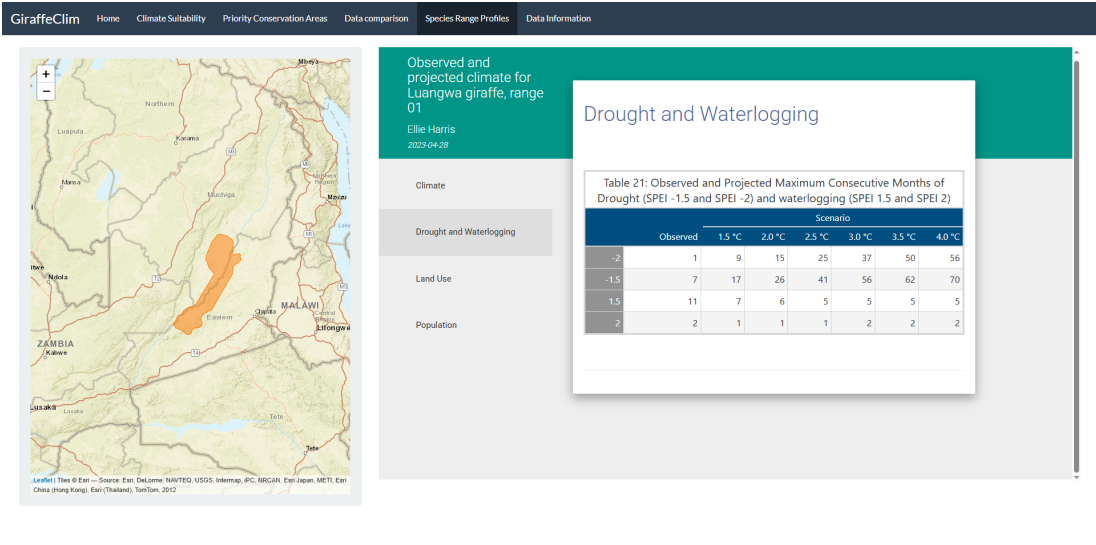


Figure 7.14: The Luangwa giraffe range in Zambia and associated range report showing the observed and projected MCM of drought and waterlogging as an average across the subspecies’ range.

The Data Comparison page of GiraffeClim shows that the central portion of the geographic range, in the South Luangwa National Park, has slightly shorter projections of MCM of drought compared to the northern part of the range in North Luangwa National Park. The ecological stability data shows that only 25% of the biodiversity is projected to remain at 3.6°C warming, across the geographic range – a value much lower than some of the

surrounding areas (Figure 7.15).

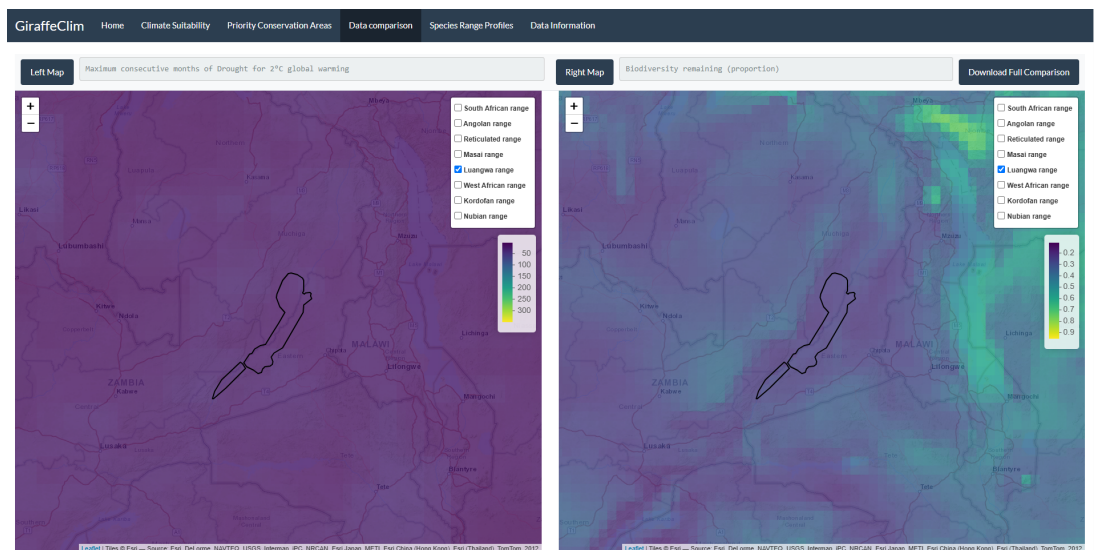


Figure 7.15: A screenshot of the GiraffeClim application, showing the Data Comparison page with MCM of drought at 2°C on the left, and biodiversity remaining at 3.6°C on the right. For both maps, yellow is the higher value and blue is lower. The Luangwa giraffe range in Zambia is shown by the black outline.

Conservation Implications

There are no publicly available conservation action plans that incorporate Luangwa giraffe. The conservation assessment for giraffe in Zambia published by the Giraffe Conservation Foundation (Ferguson *et al.*, 2022), states that degraded habitat, geographic isolation, climate-change induced drought, and natural predation from lions are key threats to the Luangwa giraffe. Based on projections of increasing drought across the geographic range of Luangwa giraffe, actions to increase available water are likely to become increasingly important for the conservation of this subspecies. The threat from predation may reduce at higher levels of global warming, as climate suitability for lions is projected to be lower in the Luangwa giraffe's geographic range even at 1.5°C. By 2°C global warming, suitable climate for lions is only projected in the outskirts of the Luangwa giraffe's range (Figure 7.16). Given the lack of data on climate suitability for this subspecies, careful monitoring is required to understand any impacts from the changing climate.

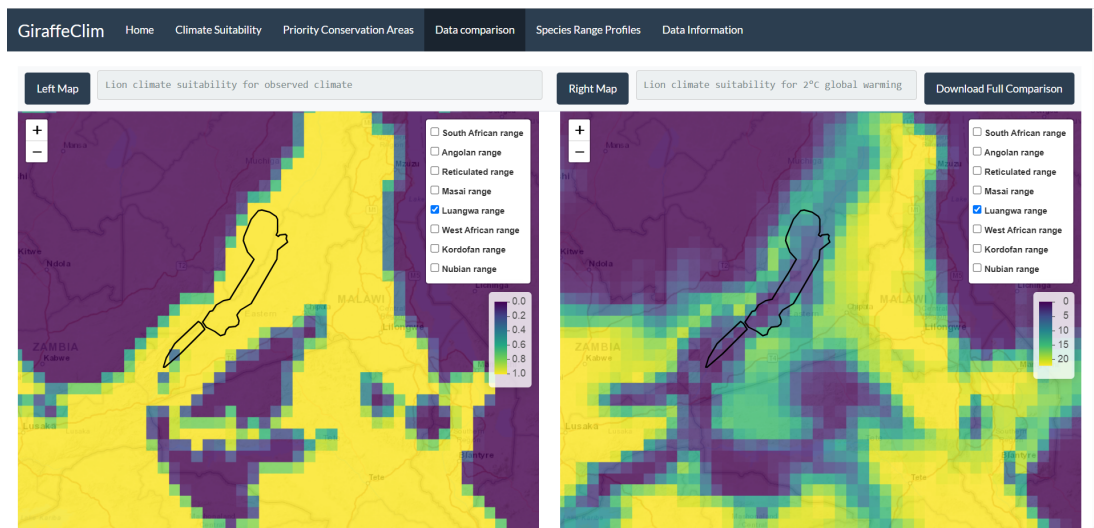


Figure 7.16: A screenshot from the 'Data Comparison' page of GiraffeClim, showing lion climate suitability projected for the observed climate period and at 2°C warming (right). Yellow indicates higher climate suitability, with purple showing low, or no climate suitability. The Luangwa giraffe's geographic range is shown in the black outline.

7.3.3 Reticulated giraffe

Reticulated giraffe (*Giraffa reticulata*) are found in Ethiopia, Kenya, and Somalia with a total population of ~16,000 individuals (Brown *et al.*, 2021). Their listing of 'Endangered' in the IUCN red list assessment is largely down to a decline of more than 50% over 30 years (Muneza *et al.*, 2018). In the upcoming IUCN red list assessment, this categorisation of 'Endangered' is expected to be kept (Giraffe Conservation Foundation, 2024).

In the Reticulated giraffe's geographic range, maximum and minimum daily temperature is projected to increase across all seasons and warming levels. The increase in maximum temperature is less than what is seen in other (sub)species. Precipitation is projected to increase in all seasons except for June-August, where a slight decrease is projected. This season, as a median across the Reticulated giraffe's geographic range, has the lowest observed average seasonal precipitation at 2 mm. There are projected to be very slight increases in both severe waterlogging and severe drought at increasing global warming levels.

The climate suitability models project that areas in the western portion of the Reticulated giraffe's range may retain suitable climate at higher warming levels than other areas (Figure 7.17), and can act as climate refugia for this species. Other areas of climate refugia are in the southeast and northeast of the range. The sensitivity analyses largely project the same areas

as climate refugia but show a slight increase in the amount of climate refugia towards the northern and western parts of the range, and a slight reduction in the southeast of the range. In the observed climate projections, both the main SDMs and sensitivity analyses project low climate suitability in the central eastern portion of the range. These findings are similar to those by Crego *et al.* (2023) who found that fine-scale habitat suitability for Reticulated giraffe was greatest in the western portions of the range. Combined, these results show the importance of the western range area in central Kenya for Reticulated giraffe.

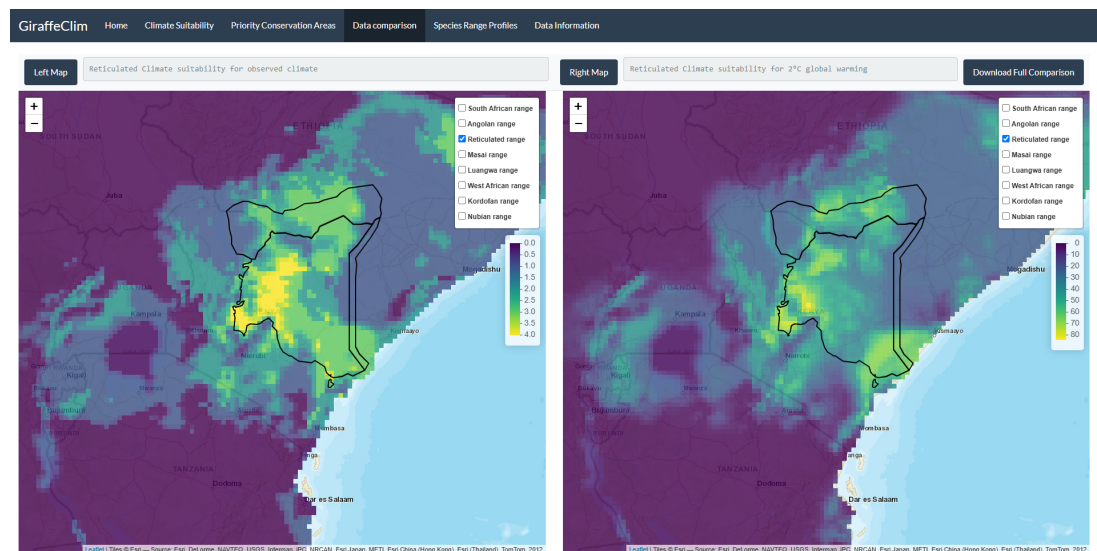


Figure 7.17: The climate suitability for Reticulated giraffe for Observed climate (left) and projected climate at 2°C (right). Reticulated giraffe range is shown by the black outline.

The Zonation rank maps show the southwestern area of the Reticulated giraffe's range (Laikipia county) as ranking the lowest at 1.5 and 2°C, despite it having some of the highest Acacia and non-Acacia food species richness compared to the rest of the geographic range. The inputs show this area to have some of the highest levels of gHM and human population, which likely caused this low ranking. The eastern portion of the range in Wajir county also has a low rank at most warming levels. Examining the input data in GiraffeClim, it is clear that this area has several factors contributing to its low rank – low climate suitability for Reticulated giraffe, comparatively low species richness for Acacia and non-Acacia food species richness, and some areas of relatively high human population.

Conservation Implications

The second edition of the National Recovery and Action Plan for giraffe in Kenya (Kenya Wildlife Service, 2023) for 2023-2027 states that threats for Reticulated giraffe include

drought, habitat degradation, fences, and poaching. Some of the activities listed in the report are to map current and potential giraffe conservation areas, produce a threat map, determine priority areas for giraffe conservation, and develop site-specific translocation plans.

The Zonation outputs from this thesis can be used as an addition to the threat maps that are being generated for giraffe in Kenya. For example, Laikipia and Wajir counties have the lowest conservation priority ranking areas across the reticulated giraffe's geographic range at multiple warming levels. Whilst this should not necessarily outweigh considerations of present-day threats happening at a finer spatial scale, it is indicative of areas with higher potential threat from climate change and anthropogenic impacts in the future. Alternatively, given that the higher levels of gHM are one of the main driving factors behind the low-ranking areas in Laikipia county, these areas could be targeted for habitat restoration where applicable. The Melako and Songa community conservancies in Marsabit county and Sera community conservancy in Samburu County have a high conservation priority ranking at both 1.5 and 2°C of warming. These are priority areas for Reticulated giraffe conservation at multiple warming levels and highlight the importance of community conservancies in Kenya for the conservation of Reticulated giraffe – something which is also mentioned in the National Recovery and Action Plan.

The Ethiopian conservation action plan for 2023-2027 (Ethiopian Wildlife Conservation Authority, 2023) mentions reduced rainfall and drought conditions as a concern for wildlife in the country. One of the Strategic Objectives in the report is to 'apply climate change mitigation strategies for giraffe conservation in Ethiopia'. In the Reticulated giraffe range in Ethiopia, the GiraffeClim application shows that MCM of drought are projected to increase by only 0.5-1.5% at 3.6°C warming, compared to observed values of between 5-12 months. This suggests that increasing maximum durations of severe drought conditions may not be too severe, but adaptation measures could be taken if this projected increase is a concern for conservation practitioners. Across all warming levels, large portions of the Reticulated giraffe's geographic range in Ethiopia have a high priority rank, and the eastern portion of this range is also an area of climate refugia for Reticulated giraffe. Given this, the range area in Ethiopia is an important conservation priority for Reticulated giraffe. Currently, Reticulated giraffe range in Ethiopia overlaps with only one protected area – Grailie

National Park, and the rest of the geographic range is unprotected. Therefore, the activities in the action plan for Ethiopia which pertain to increased patrol efficiency in protected areas and improved public awareness of giraffe are particularly important.

7.3.4 Northern giraffe

Northern giraffe (*Giraffa camelopardalis*) are found across Niger, Cameroon, Central African Republic, Chad, South Sudan, Uganda, Ethiopia and Kenya. This species has the fewest individuals of any giraffe species at just under 6,000 (Brown *et al.*, 2021). It is expected that a 2025 update to the IUCN red list assessment would categorise Northern giraffe as ‘Critically Endangered’ (Giraffe Conservation Foundation, 2024, accessed 27.04.2025)

West African giraffe

The West African giraffe (*G. c. peralta*) is found only in Niger and has an estimated population of 600 individuals (Brown *et al.*, 2021). In the current red list assessment it is categorised as ‘Vulnerable’ (Fennessy *et al.*, 2018).

Seasonal average maximum daily temperature is projected to increase throughout the West African giraffe range at all levels of global warming, and the seasonal average minimum temperature is projected to increase at a rate higher than all other (sub)species. For both of these variables, the range reports for West African giraffe show that these projections of increased temperature are largely outside of the experienced climate. For example, even at 1.5°C global warming, out of the 30 years that this warming level is centred on, over 50% of years are projected to exceed two standard deviations of observed seasonal average maximum temperature for the March-May, June-August, and September-October seasons (as an average across the subspecies’ western geographic range). In the same area, over 30% of years are projected to exceed two standard deviations of seasonal average minimum temperature at 1.5°C global warming compared to the baseline period.

In the observed period (1961-1990), average seasonal rainfall is lowest in the December-February and March-May seasons. There is no projected change in precipitation across the West African giraffe’s geographic range for these seasons, even up to 4.5°C. In the June-August and September-November seasons, which have higher observed rainfall, precipitation is projected to increase at every global warming level. The

MCM of severe drought is projected to increase at all warming levels, even by 1.5°C global warming. At 2°C global warming, 100% of the West African giraffe's range is projected to experience novel climate conditions for this subspecies.

The Northern giraffe climate suitability outputs show large areas of climate refugia in and around the West African giraffe's current geographic range. Only small areas of the geographic range are not climate refugia (Figure 7.18). The sensitivity analysis showed that including historical occurrence records in SDMs projects a much larger area of suitable climate for Northern giraffe, and in these models the entire range of West African giraffe acts as climate refugia. The climate projections for Northern giraffe are therefore likely conservative, but informative as a least-regrets method of identifying suitable climate.

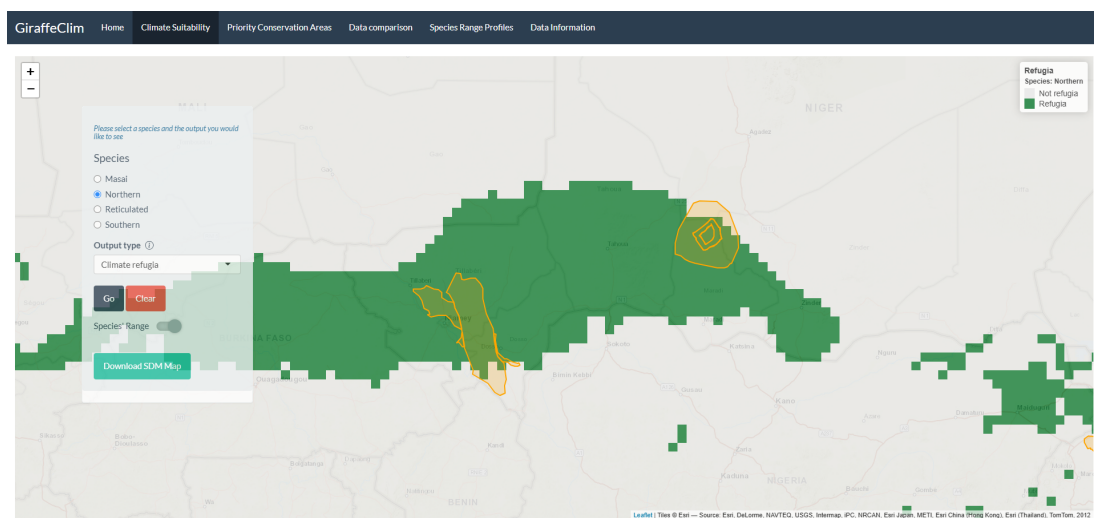


Figure 7.18: The climate refugia (green) for Northern giraffe near the West African giraffe's range (orange) in Niger.

The Zonation analyses show that areas of West African giraffe range north of Niamey and near the Gadabeji Game Reserve rank highly across multiple warming levels, until 3.6°C. The western range has lower projected MCM of severe drought but higher human modification and Acacia food species richness (Figure 7.19).

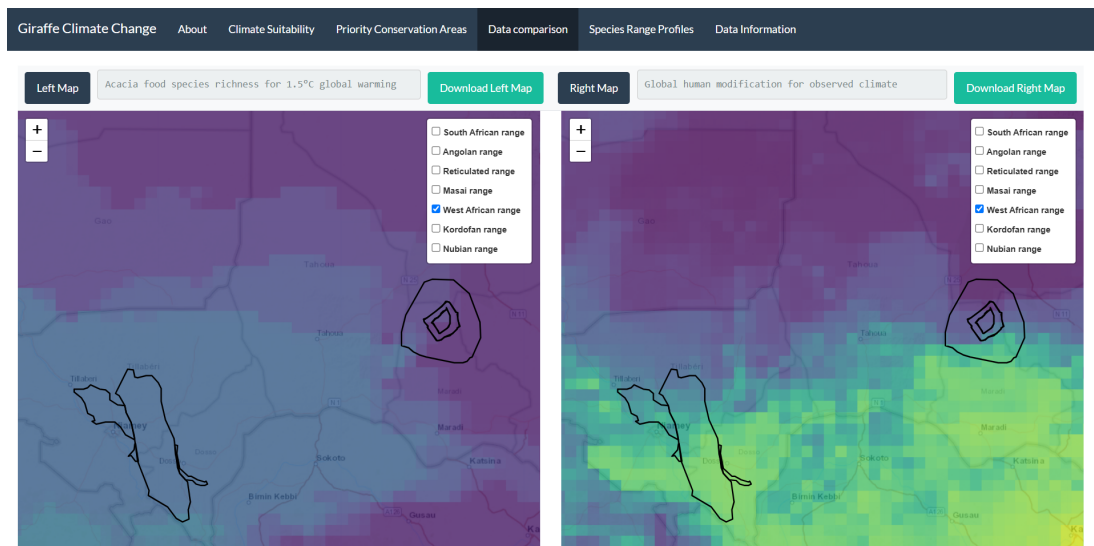


Figure 7.19: Acacia food species richness (left) and gHM (right), with both showing higher values in the western portion of the West African giraffe's geographic range

Conservation implications

Niger was the first country to have a National Conservation Action Plan for giraffe; the latest available conservation action plan for Niger was published in 2016 and has a specific section on climate change (Mallon, 2016). Relevant actions within this section include identifying sites at a national level for giraffe conservation and carrying out reforestation operations using species eaten by giraffe. Additionally, a recent review suggests that conservation actions should include projections of future geographic range expansion (Gašparová *et al.*, 2024).

The reforestation of degraded habitat with food species for giraffe can be guided by the Acacia and non-Acacia food species richness data shown in GiraffeClim. Up to 3.6°C warming, the highest species richness for both these food species groups is the West African giraffe range near Niamey, and surrounding areas (Figure 7.20). Niger also has a project, the 'Niger Acacia Senegal Plantation Project', which aims to restore degraded habitat in Niger. *Acacia senegal* (also called *Senegalia senegal*) is one of the Acacia species included in the species richness layers, and data shows climate is projected to remain suitable for this species in the area surrounding Niamey, up to 3.6°C warming.

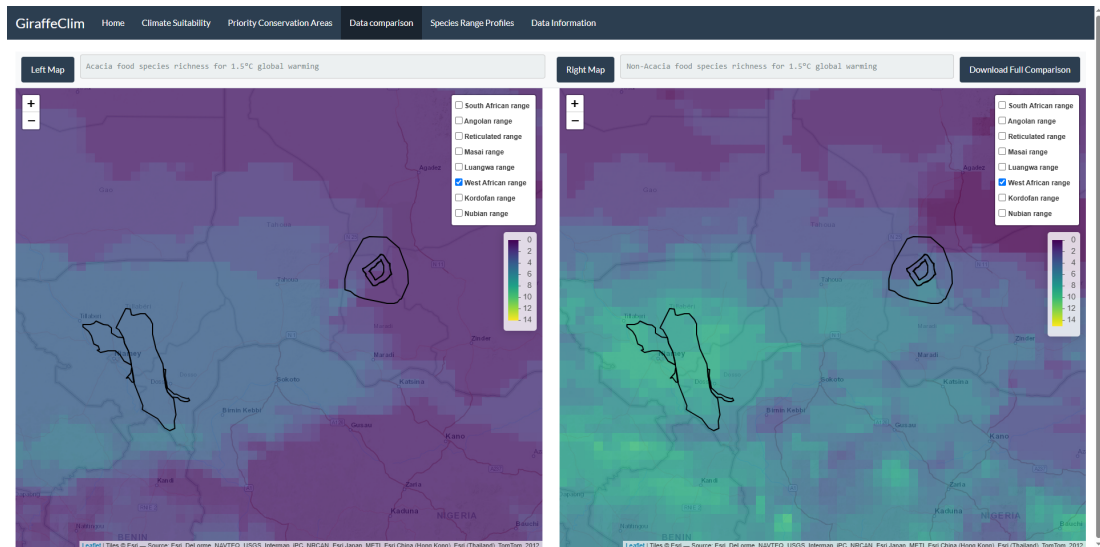


Figure 7.20: Acacia (left) and non-Acacia (right) food species richness at 1.5°C warming, centred on the West African giraffe range (black outline)

The Zonation analysis extended to areas of climate refugia for West African giraffe can aid in identifying areas outside of the current range for reforestation and conservation efforts. When extended outside the current geographic range, the highest-ranking area within Niger is north of Niamey (Figure 7.21). Recent updates of giraffe range maps suggest this area may have giraffe present (Giraffe Conservation Foundation, 2024b).

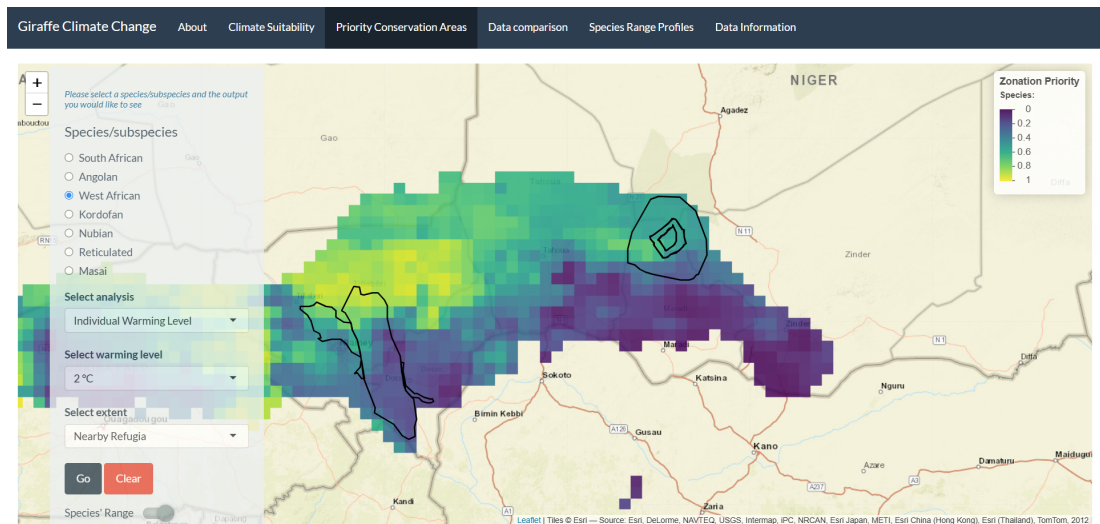


Figure 7.21: Zonation output for West African giraffe at 2°C, where values are on a scale of high priority (yellow) to low priority (blue). The West African giraffe range is shown by a black outline.

Kordofan giraffe

Kordofan giraffe (*G. c. antiquorum*) are found in Cameroon, Central African Republic (CAR), Chad, Democratic Republic of Congo (DRC), and South Sudan, and total just over 2,000 individuals (Brown *et al.*, 2021). A 2020 assessment showed that Kordofan giraffe populations were, at the time, increasing in Chad, DRC, and Cameroon, but decreasing in CAR (Brown *et al.*, 2021). On the IUCN red list, Kordofan giraffe are categorised as 'Critically Endangered' (Fennessy and Marais, 2018).

Climate projections across the Kordofan giraffe range show an increase in maximum and minimum temperature at every projected global warming level. Projections of precipitation at each warming level show only a slight median increase across the geographic range of Kordofan giraffe in the December-February and March-May seasons. The June-August season has a large projected increase in precipitation at each warming level. MCM of severe drought is projected to increase across the Kordofan range. By 2°C warming, 82% of the geographic range is projected to experience novel climate conditions, outside the bounds of what is currently experienced across the entire subspecies' range.

The climate suitability projections show that Kordofan range in Cameroon and Central African Republic has low climate suitability levels by 1.5°C global warming. Similarly low levels of climate suitability are projected for these ranges with 2°C warming. The geographic range areas for Kordofan giraffe which retain the highest level of climate suitability across all warming levels are in northern Cameroon, Chad, and South Sudan, but the only areas of climate refugia for Kordofan giraffe within their current range are in South Sudan and Chad. The sensitivity analysis does however, project a larger area of suitable climate when historical occurrence records are used in SDMs; in these models, Kordofan giraffe retain areas of climate refugia in all countries that they are found. These SDMs do nonetheless show similar patterns to the main SDMs, where climate in the southern part of the range becomes less suitable over increasing warming levels. In the sensitivity models, the only current range areas which are not projected to be climate refugia for Kordofan giraffe are in Cameroon and the Central African Republic.

The Kordofan giraffe range in South Sudan ranks highest in all Zonation analyses and warming levels. This area has one of the highest gHM levels compared to other areas in the

geographic range, but it also has the highest food species richness across warming levels and food species retention up to 3.6°C warming (Figure 7.22). The northern Kordofan giraffe range in Central African Republic also ranks highly, and when the Zonation analysis is extended to include areas of climate refugia, this area and climate refugia in South Sudan still rank highest.

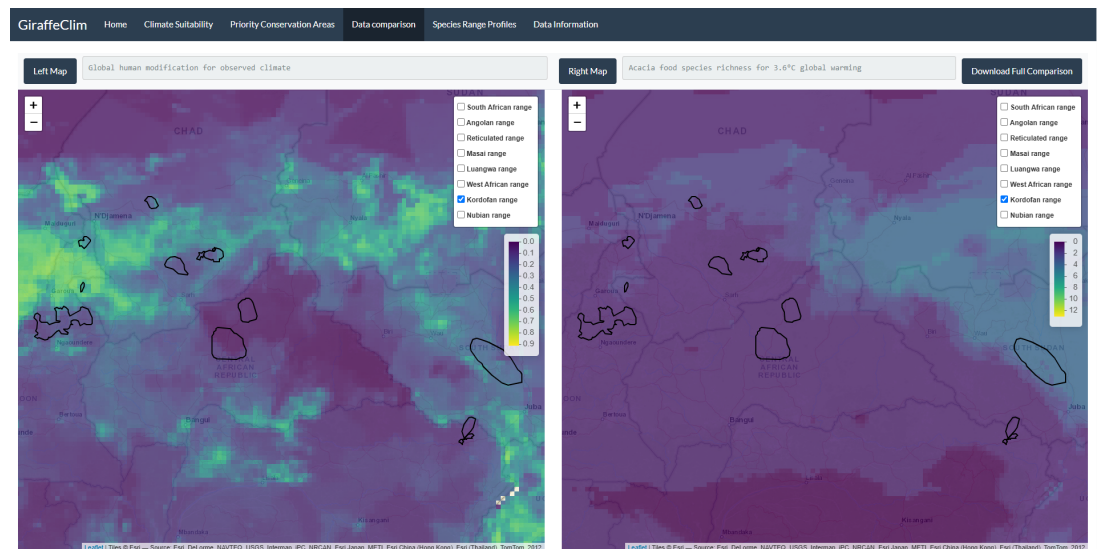


Figure 7.22: gHM (left) and Acacia food species richness at 3.6°C (right), centred on Kordofan giraffe range (black outline).

Conservation implications

There is a national conservation action plan in place for Kordofan giraffe in Chad (Ministère de l'Environnement, de la Pêche et du Développement Durable, 2024), and as recently as February 2025, giraffe monitoring efforts in the country have increased through GCF's Twiga Tracker Initiative (Giraffe Conservation Foundation, 2025). The action plan details concerns about the impact of climate change on the availability and quality of resources for giraffe, and how this may affect their distribution and subsequent management. One of the goals of the action plan is to increase the distribution of giraffe to favourable areas, specifically by repopulating priority habitats. Several areas are explicitly mentioned as priority zones for giraffe: Ennedi, Sena Oura NP, Binder-Léré/Zah Soo NP, and Manda NP. The action plan specifies that these areas should be evaluated for threats and forage availability. The Ennedi Plateau is in northeastern Chad, and whilst petroglyphs suggest there may have been giraffe in the area several thousand years ago (Keding *et al.*, 2007), the climate models produced in this thesis show that it is currently outside the bounds of suitable climate for Northern giraffe. Sena Oura is a UNESCO Biosphere reserve

in southern Chad, on the border with Cameroon. It has a low priority ranking in the Zonation outputs compared to more northern areas in Chad at all warming levels, although the rank does increase at the highest warming levels. The area loses Acacia and non-Acacia species richness even at 1.5°C warming, but drought levels are projected to be roughly the same as other Kordofan giraffe geographic range in Chad. The Binder-Léré Faunal Reserve Complex of Protected Areas (CAPBL), which already hosts a giraffe population, is the southeasternmost range of Kordofan giraffe in Chad. It ranks very low in Zonation outputs, so for it to be considered for further giraffe translocations, it may need a management plan involving increased adaptation effort to sustain giraffe under future warming levels. Instead, translocations could be made to bolster populations in higher ranking areas, such as Zakouma NP. Using the Ecological Stability data on GiraffeClim, it seems that the main threats posed by the highest levels of warming at 2100 in Binder-Léré, compared to other Kordofan giraffe range in Chad, are a loss of Acacia species richness, increase in drought, and increase in human population.

The Zakouma NP holds ~58% of the entire Kordofan giraffe population and as such is a priority conservation area (Ministère de l'Environnement, de la Pêche et du Développement Durable, 2024). The climate is projected to be suitable in this area until 2°C global warming when the eastern area becomes less climatically suitable. Given that the park is suitable for giraffe presently, the observed Zonation outputs do not necessarily need to be examined, although it should be noted that the eastern portion of the NP shows higher levels of human modification of terrestrial systems, potentially making it less suitable for giraffe. Nonetheless, the ecological stability outputs and Zonation outputs for higher global warming levels can provide useful information on the potential impact of climate change. At each warming level, the eastern side of Zakouma NP ranks lower than the western portion. This is in part due to higher human modification, but also lower climate suitability, and projected loss of non-Acacia food species at higher warming levels. In Zakouma NP, giraffe and buffalo make up a majority of lion diet (Fratlicelli *et al.*, 2024). The projections of suitable climate for lions shows that by 2°C, only small areas to the west of the NP remain suitable. Shifts in climate suitability for both species may impact predator-prey dynamics, and if both populations were to come under stress from changing climate conditions, careful monitoring would be needed to ensure the giraffe population remains stable. The species range report, available on GiraffeClim, can also be used by the

management team to investigate the projected climate changes in this area and plan any adaptation and monitoring actions accordingly (Figure 7.23).

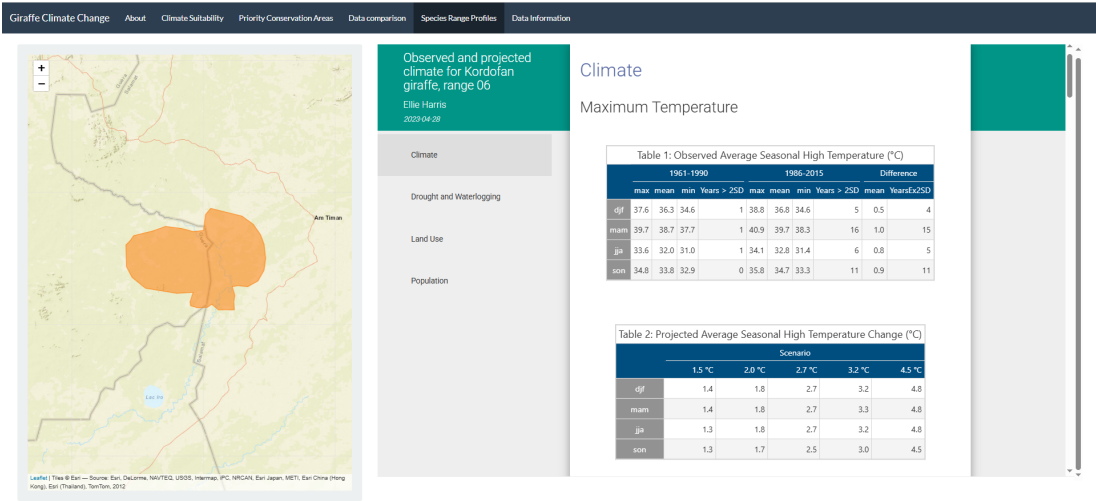


Figure 7.23: The Kordofan range in Zakouma National Park, and the associated species range profile. Screenshot from the GiraffeClim application.

The Kordofan giraffe population in the Democratic Republic of Congo (DRC) is found exclusively in the Garamba NP (GNP) in the north of the country. A previous National Conservation Strategy and Action Plan for DRC (Garamba National Park, 2018) for 2018-2020 aimed to increase the population to 60 individuals, and planned actions included threat assessments within the park and specific investigations into predation as the main threat. The lion climate suitability layers show very low climate suitability for lions in GNP under the observed climate. Given predation by lions is listed as a key threat to giraffe in Garamba, the lion models may not be robust enough to use in informing climate suitability in this area. However, lion climate suitability is projected to generally decrease in areas near here at higher warming levels. For northern giraffe, however, climate is projected to remain suitable until the highest warming level explored – 3.6°C. This may result in a shift in lion distribution and decrease of predation on giraffe in GNP. The Zonation priority rankings show that all areas of the GNP have a similar rank across all warming levels, but when examining the ecological intactness output, the central area of the park ranks highest, showing it undergoes the least change at 3.6°C warming compared to the observed time period. This area retains the most food species richness at higher warming levels.

Nubian giraffe

Just over half of the Northern giraffe population is made up of the Nubian subspecies (*G. c. camelopardalis*; Brown *et al.*, 2021), which is found in Ethiopia, Kenya, Uganda, and South Sudan (O’connor *et al.*, 2019). The 2018 IUCN red list assessment categorises Nubian giraffe as ‘Critically Endangered’ due to the decrease of 95% of its population over the previous 30 years (Wube *et al.*, 2018).

Nubian giraffe are projected to experience an increase in maximum and minimum temperatures at all global warming levels, but this increase is projected to be lower than for the other subspecies of Northern giraffe. Across the Nubian giraffe’s entire geographic range, an increase in precipitation is projected in three seasons (December-February, March-May, and September-November), but in the June-August season some areas are projected to have a decrease in precipitation whilst others are projected to see an increase. Whilst the median value across the Nubian range suggests little to no change in MCM of severe waterlogging at increasing global warming levels, the maximum value in the Nubian giraffe’s range shows an increase in MCM of waterlogging greater than any other (sub)species at all warming levels. MCM of severe drought is also projected to increase across some of the geographic range, but at much lower levels compared to the West African subspecies.

Species distribution models show that the Nubian giraffe’s geographic range remains largely climatically suitable under all warming levels examined. The areas with the highest level of climate suitability are those in South Sudan, Ethiopia, northern Uganda, and Kenya. The sensitivity analysis where SDMs included historical giraffe occurrence records supports this, along with slight increases in the amount of refugia projected in Ethiopia. Both the main SDMs and those modelled with historical occurrence data show that some of the smaller, more fragmented ranges (in Ruma NP and Mwea National Reserve in Kenya, and southern Uganda near the Tanzanian border) have the lowest climate suitability and are projected have unsuitable climate by 2°C global warming. Murchison Falls NP in Uganda is projected to see a decrease in suitable climate in a small area to the west of the park at 1.5°C warming. By 2°C warming, the westernmost portion of the range becomes largely unsuitable. However, the eastern portion of the park is projected to remain climatically suitable for Northern giraffe until at least 2°C warming.

Across all Zonation analyses, the highest-ranking priority areas are the Kidepo valley in Uganda and the large range area in South Sudan. The ecological stability analysis shows that some of the areas projected to lose Acacia species richness are Murchison Falls NP (Uganda), Pian-Upe (Uganda), Omo NP (Ethiopia), and Ruma NP (Kenya). The Nubian giraffe geographic range in South Sudan is projected to have the largest MCM of drought, and the ranges closest to the Kenya-Uganda border are projected to have the longest MCM of waterlogging. The Kenyan ranges other than Ruma NP and Mwea NP are projected to retain the largest proportion of species richness under 3.6°C warming. The highest-ranking areas for ecological stability for Nubian giraffe are Lake Nakuru NP and immediately surrounding areas in Kenya, Bandgilingo NP in South Sudan, and Kidepo valley in Uganda.

Conservation implications

There are national conservation action plans in place for Kenya, Ethiopia, and Uganda that have implications for the conservation of Nubian giraffe.

The Ugandan action plan for 2020-2030 (UWA, 2020) has five strategic objectives, which include enhancing the resilience of giraffe populations in Uganda, and promoting the use of scientific, evidence-based data in the management of giraffe. Desired outputs from this action plan are habitat suitability studies, environmental and social impact assessments for the recommended translocation sites, the translocation of giraffe into these areas (post-assessment and approval), identification of potential movement corridors, effectively marked boundaries for protected areas, and ensuring the establishment of sufficient water points in water-stressed range areas.

All of Uganda is currently climatically suitable for Northern giraffe, although northern Uganda has the highest level of climate suitability. Research published in 2019 showed that 90% of the Nubian giraffe population in Uganda was found in Murchison Falls NP, and stressed the need for translocations to form new populations and bolster existing ones outside of Murchison Falls (Brown *et al.*, 2019). Since 2016, there have been several successful translocations of giraffe in Uganda. Two of these translocations moved giraffe from the northern to the southern part of Murchison Falls, due to the threat of oil exploration in the northern parts (Giraffe Conservation Foundation, 2017). This threat of oil drilling has resulted in more recent translocations to establish populations outside of

Murchison Falls NP, to Pian Upe where giraffe had gone locally extinct due to civil unrest, and Kidepo Valley where giraffe populations were small and needed bolstering (Giraffe Conservation Foundation, 2018, 2020). The climate suitability data in this thesis shows that the western portion of Murchison Falls NP, and Lake Mburu NP, are projected to become largely unsuitable for Northern giraffe by 2°C global warming. Translocations are therefore of additional importance and should be considered for areas of climate refugia.

Existing Nubian giraffe ranges in Uganda which are considered climate refugia are Kidepo Valley and Pian-Upe (Figure 7.24). Areas of external climate refugia (those outside of current giraffe geographic range) include Iriri Community Wildlife Management Area, Bokora Corridor WR, Matheniko WR, and Karenga Community Wildlife Management Area. These protected areas are also ranked as a high conservation priority for Nubian giraffe in the Zonation analyses under global warming levels of up to 2.7°C, at which point Iriri and Pian-Upe are not considered priority areas. Nubian giraffe were previously found in Matheniko and Bokora Corridor, but were extirpated due to poaching in the areas (UWA, 2020). Conditional on finer-scale investigations of habitat suitability, the analyses in this thesis would suggest that these areas would be suitable, from a climate change perspective, for translocations.

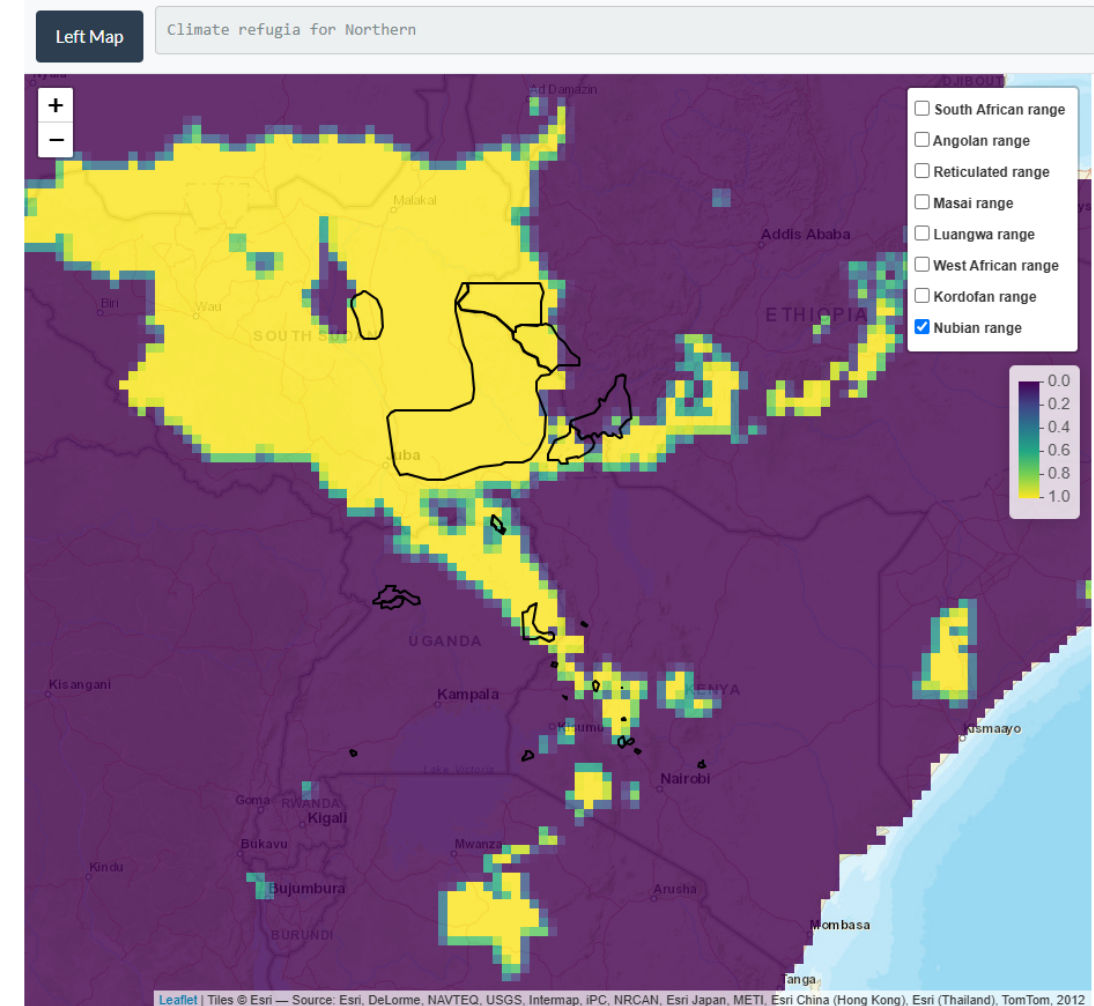


Figure 7.24: Screenshot of GiraffeClim application showing areas of climate change refugia (yellow) for Northern giraffe, centred on the Nubian giraffe range (black outline).

The Ethiopian conservation action plan (mentioned previously in the context of Reticulated giraffe) states that the Gambella NP is a conservation priority for both Nubian giraffe and other wildlife in Ethiopia (EWCA, 2023). The report details habitat loss (caused by subsistence and commercial agriculture) and human population growth as a large threat to the NP, with poaching from bordering human populations an on-going issue. The population in Ethiopia is projected to increase from <150 million currently to almost 400 million by 2100 (UN DESA, Population Division, 2024). In Gambella NP, projections of human population under SSP2 show an increase from ~71,000 to ~104,000 people between 2020 and 2100 (Gao, 2020). Extending this to a further 15 km buffer, numbers are much higher with projections showing ~240,000 people in 2020 and ~338,000 people in 2100. Gambella NP is an area of climate refugia for Northern giraffe, but MCM of drought in the

area are projected to increase even at 1.5°C global warming. Adaptation efforts may be needed to sustain the giraffe population in Gambella, given projected drought conditions. Omo NP, south of Gambella, is projected to see shorter MCM of drought at each warming level, but very little of the area is considered climate refugia for Northern giraffe.

The national conservation action plan for giraffe in Kenya (KWS, 2023) states that translocations of Nubian giraffe to Ruko Community Conservancy are planned following a recent, successful translocation. The northern and western portions of Ruko Community Conservancy are projected to be areas of climate refugia for Northern giraffe. The central portion, whilst not classed as climate refugia under the strict criteria in Chapter 4, nonetheless maintains relatively high climate suitability even at the highest projected warming levels. The Ruko Community Conservancy, and directly adjacent areas, are the highest-ranking priority areas in Kenya at all warming levels. A large driver of this is likely to be the higher projected levels of climate suitability and lower human modification in this area compared to other Nubian giraffe ranges in Kenya.

The national action plan states the climate change-induced water level rise in Lake Nakuru is a threat for the Nubian giraffe population in Lake Nakuru national park. The species range profiles, which can be found in GiraffeClim, indicate that precipitation in this region is projected to increase by ~5-25% in all but the June-August season at 1.5°C warming (compared to the observed climate data of 1961-1990; Figure 7.25). The Nubian giraffe population here may therefore need careful monitoring in wet periods, and if adaptive measures are not able to be taken, then translocations may be needed to other Nubian range areas in Kenya.

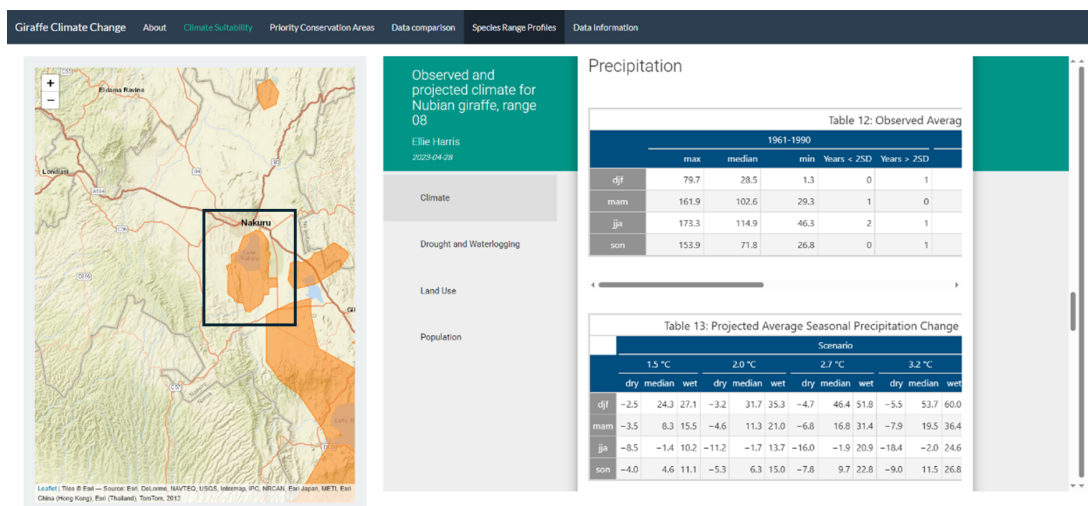


Figure 7.25: A screenshot of the GiraffeClim application, showing the range profile for the Lake Nakuru population of giraffe (black rectangle).

7.4 Scientific implications

In addition to the applied value of this thesis for giraffe conservation, there are several broader scientific implications. Firstly, it provides a clear approach for addressing multiple sources of uncertainty in species distribution models and projections of suitable climate. In Chapter 4, climate suitability was projected using 22 GCMs and four SDM algorithms, with outputs classified by agreement level across both modelling components. Comparison among SDMs revealed variation in projected suitability, and only high-agreement areas were used to identify areas of climate refugia, which themselves represent a least-regrets option that helps mitigate the uncertainty of future realised global warming levels. This workflow offers a transparent way to both manage and communicate uncertainty, and is transferable to other taxa and regions.

Secondly, the thesis contributes a complementary methodology to SDMs by quantifying climate change exposure across a species' current geographic range. This approach provides a more detailed understanding of potential drivers of change and allows conservation practitioners and researchers to engage directly with projected changes in temperature and rainfall, supporting forward planning for in-situ management and adaptation.

Thirdly, analyses that integrate multiple impacts of climate change are still relatively rare. Chapter 5 demonstrates how spatial prioritisation software can be used to incorporate

multiple climatic, biotic and anthropogenic factors, moving beyond approaches based solely on mean climate suitability. Combining climate refugia analyses with Zonation prioritisation illustrates how climate projections can be embedded within realistic conservation decision-making while retaining flexibility to explore the influence of different input layers.

Finally, the GiraffeClim application highlights the potential of interactive, web-based visualisation as part of the scientific workflow, enhancing the interpretation and communication of results.

7.5 Limitations

To make the research in this thesis more robust for conservation actions, areas of uncertainty have been reduced as much as possible. For example, to account for uncertainties in climate change projections, 22 CMIP6 General Circulation Models (GCMs) were used to project areas of suitable climate under future warming scenarios. Four SDM algorithms were used to capture differences in identifying relevant predictor variables and building statistical relationships between occurrence data and environmental data. Additionally, areas of climate change refugia were identified to provide areas of suitable climate regardless of the level of global warming reached. In the Zonation analysis, subjective influences on the choice of feature weightings were examined by running a sensitivity analysis of 1000 differently weighted runs. Nonetheless, there are some important caveats and limitations that may impact the interpretation of these results for conservation purposes:

1. **Species range contractions:** The current distribution of giraffe has been substantially reduced by human activities such as poaching, infrastructure development (for example, fences), and land-use change. Statistical SDMs typically assume that the occurrence data reflects the full species' climatic niche. However, when this assumption does not hold, which is likely the case with giraffe, projections of suitable climate may be conservative if range reduction occurred at the edges rather than the core of the species' geographic range. This issue was explored by Martínez-Freiría *et al.* (2016), who found that SDMs built with historic occurrence

data projected a much larger area of suitable climate for giraffe. Historic occurrence data were not incorporated into the main SDMs in this thesis due to the challenges and uncertainties associated with assigning the recently updated four-species taxonomy to historical records. However, to assess the potential influence of human-induced range contraction on model outputs, a sensitivity analysis was conducted in which SDMs were re-run with historical occurrence records included (presented in the Supplementary Material to Chapter 4). This analysis showed that incorporating historical records resulted in minimal changes to projected climate suitability for Masai, Southern, and Reticulated giraffe, but led to a modest expansion of the projected suitable climate area for Northern giraffe, particularly under higher warming scenarios. These results suggest that, while range contraction may lead to conservative estimates of suitable climate in some cases, the overall conclusions of this thesis regarding the location and persistence of climate refugia are robust to this source of uncertainty. Nevertheless, areas projected to be unsuitable should be interpreted with greater caution, particularly for Northern giraffe. This further supports the use of a no-regrets climate refugia framework, whereby conservation efforts are focused on areas consistently identified as suitable across scenarios, thereby reducing the impact of uncertainty associated with range contraction and historical data limitations.

2. **Uncertainty in regional climate projections:** Uncertainty in climate projections arise from multiple sources, such as uncertainty in projections of radiative forcing pathways (scenario uncertainty), modelled responses of climate to specific radiative forcings (model uncertainty), and the natural variations of the climate system (IPCC, 2023). In this thesis, the model uncertainty from General Circulation Models (GCMs) was a key consideration. Even given the same radiative forcing input, GCMs can vary in their projections of climate due to underlying differences in the structure and parameterisation of the models (Lafferty and Sriver, 2023). This uncertainty can be particularly evident in projections of mean precipitation, where models may project opposing wetting and drying trends (Fischer *et al.*, 2014). To account for model uncertainty, climate projections used in this thesis constituted more than 20 GCMs: 21 CMIP5 models were used in Chapter 3 (see Chapter 3 section 3.2.2) and 22 CMIP6 models were used in Chapter 4 and 5 (see Chapter 4 Methods section 4.2.4). In

Chapter 3, values of projected climate were given as either the ensemble mean or median (for temperature and precipitation, respectively). Additionally, in the range reports displayed on the GiraffeClim application, projected precipitation values are shown for the ensemble median, average of models projecting wetting, and average of models projecting drying. This gives additional information to the reader on model agreement in the direction of change. For SDMs projected under future climate in Chapter 4, high model agreement thresholds of at least 15 out of 22 GCMs were required for areas to be labelled as 'suitable'. Setting this threshold higher than a simple majority of 12 models ensures strong agreement between models and reduces the uncertainty. In the Zonation analyses (see Chapter 5), model agreement was specifically factored into the projections of suitable climate for giraffe and lions. For example, instead of using feature layers showing 'suitable / unsuitable' climate, the layers had values of 0-22, corresponding to the number of GCMs projecting suitable climate.

3. **Lack of reliable land-use projections:** Land-use change is a large threat to all species of giraffe (Muller *et al.*, 2018), and future land use change will likely have a big impact on giraffe populations. Incorporating reliable projections of land-use changes would make assessments of priority conservation areas more robust. The decision was made to omit land-use projections from the Zonation analyses because of the substantial uncertainties surrounding currently available data (described in Chapter 5). Inclusion of this data would have added ambiguity to the analyses and made useful interpretation of the results more difficult. To mitigate the potential impact of future land-use change on giraffe, areas of high conservation priority should be considered for protected area status (if currently unprotected), with regulations in place for governing land-use permissions. Additionally, increasing community awareness on the ecological importance and threatened status of giraffe, and the negative impact of land-use change can help improve conservation outcomes (Brooks *et al.*, 2012).
4. **Impacts from increased atmospheric CO₂ concentrations:** The ecological effects of increased atmospheric CO₂ associated with higher global warming levels are not captured in this thesis. Elevated CO₂ can cause partial stomatal closure, increased

water use efficiency (WUE), and increased rates of photosynthesis in plants (Morison, 1985; Drake *et al.*, 1997). Increased WUE in plants can reduce some of the impacts of water deficits on plant productivity, but this does not necessarily extend to extreme drought conditions (Trisos *et al.*, 2022). Over Africa, increasing CO₂ levels in combination with changes to aridity are projected to cause biomes shifts (Trisos *et al.*, 2022). In areas of increasing aridity, higher CO₂ levels are projected to cause slower rates of woody encroachment and forest die off. In contrast, where decreasing aridity interacts with higher CO₂, projections show forest expansion into savanna, a loss of savanna grassland, and grass expansion into arid shrublands (Trisos *et al.*, 2022). Additionally, in fire-disturbed landscapes dominated by grasses, increased CO₂ can speed up the regrowth of C3 woody tree saplings and allow them to become established in the landscape (Bond and Midgley, 2000). This can then impact fire regimes, reducing their frequency and intensity (Midgley and Bond, 2015). Aside from biome and landscape scale changes, increasing CO₂ may also impact the palatability and nutritional content of giraffe browse species. There is mixed evidence on whether increasing CO₂ impacts the concentration of condensed tannins; Hall *et al.* (2005) found no effect of this in three oak species and one nitrogen-fixing legume species, whilst a meta-analysis of 59 studies reporting the impact of CO₂ on plants showed a positive effect of CO₂ concentration on increased tannins (Stiling and Cornelissen, 2007). The tannin concentration in plants can impact their palatability, and research has shown that it can impact the forage decisions of giraffe (Furstenburg and van Hoven, 1994; Caister *et al.*, 2003). Additionally, increased CO₂ can negatively impact protein levels in plants, although the extent differs between species and can have an interacting effect with temperature (Bezner Kerr *et al.*, 2022).

5. **Fine-scale differences in climate suitability:** The areas of suitable and unsuitable climate identified in this thesis occur at a coarse spatial resolution of ~20 km. However, local topography and landscape features can create fine-scale climate conditions that differ from broader regional patterns (Geiger *et al.*, 2009). This can result in areas having unsuitable or suitable climate for giraffe even when the projections suggest otherwise. The coarse-resolution projections in this thesis are valuable nonetheless – they provide a useful macroecological perspective of

broad-scale patterns of climate suitability, which is particularly useful for a species such as giraffe with large home range requirements.

6. **Interpretation of Zonation priority rankings:** The output of the Zonation analysis as a continuous ranking of conservation priority was a deliberate choice because of the utility in understanding which areas are both highest and lowest ranking, as opposed to methods which only select the highest-ranking areas. However, there is an important caveat – the priority ranking does not equate to habitat suitability. High priority areas are those with the best relative balance of high positive and low negative features in the study area, but they may still face significant threats or lack sufficient forage to support giraffe populations (for example). There is a risk that conservation actors may misinterpret high-ranking areas as inherently secure under climate change scenarios, when in fact they may still require adaptation effort to ensure the persistence of giraffe populations in the area. It is recommended, therefore, that priority rank maps are always interpreted alongside the underlying input data, all of which are available in GiraffeClim. In addition, there is an inherent element of subjectivity in the Zonation analyses due to the user-defined weightings for feature layers. The extent of influence of this on the Zonation outputs was examined through a sensitivity analysis and the results showed a high degree of robustness in cell priority scores across different weighting schemes. Nonetheless, some degree of variation was observed, highlighting the importance of transparency in weighting decisions and the need for interpretation of the results in the context of these choices.

7.6 Future research

Future research could explore several avenues to complement and build upon the findings in this thesis. Specifically, collecting fine-scale data on the behavioural and physiological responses of giraffe to climatic variability, alongside finer-resolution assessments of habitat suitability, and the integration of local knowledge into conservation planning, would allow more comprehensive, mechanistic understandings of the vulnerability of giraffe to climate change.

Future work could prioritise the collection of continuous, individual-level datasets that

directly capture how giraffe respond to climate and climate changes in situ. This would include high-resolution GPS and accelerometry data to quantify fine-scale movement patterns, habitat selection, and activity budgets, collected alongside detailed information on time of day, season, and local climatic conditions. Such data would allow for the identification of behavioural responses to climatic variation, including changes in movement rates, foraging behaviour, shade use, and temporal shifts in activity that may enable giraffe to cope with increasing temperatures or altered precipitation regimes.

In parallel, detailed physiological monitoring could provide useful information on the mechanisms underlying these behavioural responses. This could include measurements of core and skin temperature, heart rate, hydration status, and indicators of physiological stress, collected across seasons and climatic gradients. Despite a growing body of literature on giraffe physiology (see Mitchell, 2021), key uncertainties remain regarding upper limits of heat tolerance, water (in)dependence, and the extent to which these traits vary among species or populations. Collecting such data during periods of climatic extremes, such as heatwaves or droughts, would be particularly valuable for assessing physiological thresholds, acclimation capacity, and the degree of behavioural and physiological plasticity that may allow giraffe to persist even under novel climatic conditions.

Coupling these behavioural and physiological datasets with fine-scale climatic data collected at high spatial and temporal resolution would allow for a more mechanistic understanding of giraffe responses to climate. This, in turn, could facilitate the development of mechanistic species distribution models that map climate suitability based on physiological limits rather than correlative relationships alone (Kearney and Porter, 2009). Such models would improve projections of climate suitability under future warming scenarios and provide a stronger basis for evaluating the effectiveness of targeted conservation interventions.

Additionally, if these data were collected at sufficiently fine spatial scales, future research could complement the broad-scale climate suitability assessments presented in this thesis with fine-scale analyses of habitat suitability, such as those by Crego *et al.* (2023) and Muthiuru *et al.* (2024). This approach would be particularly valuable for giraffe populations with limited dispersal ability due to protected area boundaries or habitat fragmentation. Where fine-scale climate data are unavailable or unreliable, alternative

approaches incorporating elevation and lapse rate could help identify microrefugia within coarse-resolution grid cells that may retain suitable climatic conditions longer than surrounding areas. Identifying such areas could highlight locations where giraffe may persist despite broader regional declines in climatic suitability.

Finally, integrating detailed local knowledge of planned developments, land-use change, infrastructure, and management capacity with climate projections from this thesis could further enhance future conservation planning. This would support the development of spatially explicit, localised individual-based models (IBMs), such as that developed by Bond *et al.* (2023), enabling conservation practitioners to anticipate the combined impacts of climate change and anthropogenic pressures and to design interventions that are tailored to the specific mechanisms driving vulnerability in different giraffe populations.

7.7 Conclusions

The research outputs from this thesis have important implications for the conservation of giraffe at species-wide and regional scales. Each species' exposure to climate change has been examined, and priority areas most robust for giraffe against changing climatic and anthropogenic factors have been identified. Encouragingly, all species retain regions of climate refugia within their current geographic ranges. Given that refugia have been defined to account for uncertainty in climate models and multiple climate change scenarios, prioritising these areas as part of a no-regrets conservation strategy offers a pragmatic way to buffer against the uncertainties surrounding future realised global warming levels. The insights from the Zonation analyses add a further layer of robustness for giraffe conservation, accounting for multiple dimensions of climate change impact and anthropogenic threats. These conservation priority rank maps serve as a valuable resource for conservation practitioners, policymakers, and researchers, helping to bridge the gap between large-scale climate projections and actionable conservation strategies.

In the face of a changing climate and growing anthropogenic pressures, the conservation of these iconic species relies on forward-looking conservation strategies rooted in an understanding of the potential impacts of climate change. Such approaches are essential for the survival of giraffe for generations to come.

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